INKOMATI-USUTHU

CATCHMENT MANAGEMENT AGENCY

Groundwater

Resource Accounting for the Inkomati-Usuthu Water Management Area in Mpumalanga, South Africa

Implementation of the Groundwater Strategy

2023

VISION

Sufficient, equitable and quality water resources for all in the Inkomati-Usuthu Water Management Area

MISSION

To efficiently manage water resources by empowering our stakeholders in our quest to contribute towards transformation by promoting equal access to water and protecting the environment

VALUES

Integrity

Batho Pele (Stakeholders Orientation)

Accountability

Diversity

Transparency

Groundwater Resource Accounting for the Inkomati-Usuthu Water Management Area in Mpumalanga, South Africa

Implementation of the Groundwater Strategy

Report prepared by Geohydrology Sub-divion for the

Inkomati-Usuthu Water Management Agency

INKOMATI-USUTHU
CATCHMENT MANAGEMENT AGENCY

Title	Implementation of the Groundwater Strategy
Authors	Study team
Project name	Groundwater Resource Accounting for the Inkomati-Usuthu Water Management Area in Mpumalanga, South Africa
IUCMA Report Number	14/1/1/1
Status of Report	Final Report
Study team	IUCMA geohydrology team

Approved by

Dr. T Sawunyama

Acting Executive Water Resource Manager

April 2023

1. Acknowledgement

The authors wish to extend his gratitude to:

- The Executive Water Resource Management and the office of the Chief Executive Officer, of Inkomati-Usuthu Catchment Management Agency (IUCMA), for the endorsement of the project.
- The Water Research Commission (WRC)'s Graduate Employability Programme is also acknowledged for attaching an intern who became a valuable project team member.
- The support provided by the hydrology subdivision of IUCMA in providing the streamflow, rainfall and hydrology expertise were required.
- The IUCMA at large in setting up a comprehensive and functional groundwater monitoring programme (monitoring network, staffing, databases); without data, this project would have not been possible.
- The groundwater team (namely Moses Mojabake, Stanley Ngomane, and Bokang Maletele), that worked hard to complete the project in a record time (one year).
- Mr Mamaropeng Selepe who reviewed the document.

Executive summary

Introduction

As per Peter Drucker's (Drucker 2015) infamous say that one cannot manage and plan what they cannot measure, groundwater management requires a comprehensive situation assessment which is a prerequisite step for devising informed groundwater management. In South Africa, a pioneering study that resulted in quantitative estimates of groundwater resource availability was the 1995 national Groundwater Resource Assessment One (GRA I). The update of GRA I was instituted and completed in 2006 through the GRA II; consequently, the year 2022 marks a sixteen-year anniversary of the GRA II. In between 2006 and 2022, South Africa experienced a 2015/2016 drought that was termed one of the worst drought in the last 50 years (Monyela 2017). Additionally, groundwater reliance has grown drastically. For example, in response to the 2015/2016 drought, farmers, households, businesses and national governments adopted reactive solutions which involved extensive "panic" drilling of boreholes across the country. This increased use of groundwater inevitably continued after the said drought because installation of wells and the infrastructure for delivery of groundwater are a considerable investment. Consequently, it was imperative and indispensable that the groundwater resource accounting be updated. To that end, the aim of this study is to provide updated quantitative estimates of regional groundwater budgets of the Inkomati Usuthu WMA.

Methodology

To address the set aim, the study followed a classical groundwater volume accounting approach establishing the balance between quantitative estimates of:

- groundwater recharge,
- groundwater contribution to stream flows (baseflow),
- draft (combined human and transpiration abstractions) and
- changes in groundwater storage.

Except for groundwater draft, all the components of the groundwater balance were calculated from field data set (e.g., groundwater levels, rainfall, streamflow data); consequently, draft was calculated as an unknown variable of the equation:

- Groundwater contribution to stream flow was estimated through a baseflow separation using the BFI+ 3.0 module (build 6) of HydroOffice 2010 software. In the software, a low pass filter recursive digital filter (RDF) method was used. Based on the assumption that the outflow from an aquifer is linearly proportional to its storage, the RDF based on Eckhardt (2005) digital filter was used.

- Groundwater recharge was calculated based on the modification of water table fluctuation method by Healy and Cook (2002) which requires the groundwater level data and estimates of storage coefficients. The storage coefficients were estimated using a formulation by Hannula et al. (2003) that relates four parameters namely, streamflow rate, recession constant or depletion factor, average groundwater stage and a catchment (drainage) area.
- The groundwater storage change was estimated based on the published relationship between groundwater level fluctuation, storage coefficient and drainage area, based on the formulation referenced to Koïta et al. (2018). The formulation estimates the change in storage as a product of catchment area, storage coefficient and change in groundwater level.

Estimates of the groundwater balance components were then used to estimate the groundwater potential, groundwater footprint and groundwater stress conditions.

- Groundwater potential was calculated using a formulation that combines groundwater recharge (± the groundwater budget imbalance depending on whether there is mountain block recharge or capture where the plus was used for the former wherein baseflow is greater than groundwater recharge and the minus was used for the latter), draft and basic human needs.
- Groundwater footprint and groundwater stress conditions were estimated using a formulation modified from Gleeson et al. (2012) and Smakhtin et al. (2004) respectively. The formulation relates catchment area, draft, groundwater recharge (± the groundwater budget imbalance) and baseflow.

Results

- Baseflow
    - At 891.32 Mm^3/a, Komati has the highest baseflow contribution compared to Usuthu (381.13 Mm^3/a) whilst that of Crocodile and Usuthu are 170.33 Mm^3/a and 107.57 Mm^3/a respectively.
- Draft and change in storage.
    - On average, Usuthu and Komati catchments experienced positive change in groundwater levels corresponding to an approximated change in storage of 16.68 Mm^3/a and 17.54 Mm^3/a respectively.
    - Both crocodile and Sabie-Sand are characterised by negative groundwater storage change of -4.41 Mm^3/a and -3.65 Mm^3/a respectively linked to the declining groundwater levels across the catchments.
    - At 516.69 Mm^3/a, the draft for Crocodile was the highest followed by Sabie-Sand at 214 Mm^3/a.

- At 35.09 Mm^3/a, draft for Komati catchment is about 1.73 Mm^3/a more compared to Usuthu (Fig. 20).
- Compared to the WARMS data, the draft is 32.31 Mm^3/a more for Usuthu and 15.44 Mm3/a more for Komati whilst that of Crocodile and Sabie-Sand are 513.89 Mm^3/a and 211.36 Mm^3/a respectively.
- The difference between the draft and the WARMS data potentially represents transpiration magnitudes; consequently, Crocodile is characterised by the highest transpirations followed by Sabie-Sand due to high density of forestry plantations in these catchments compared to Komati and Usuthu.

- Groundwater recharge
    - Groundwater recharge for Komati ranges between 2.11% and 8.86% and averages 4.86% whilst it ranges between 1.17% and 5.83% for Usuthu with an average of 3.5%.
    - Groundwater recharge averages for Crocodile and Sabie-Sand are 6.62% and 3.50% respectively.
    - Komati receives the highest groundwater replenishment of about 909 Mm^3/a compared to the 398 Mm^3/a of Usuthu .
    - Compared to the 2006 GRA II estimates, groundwater recharge has dropped by approximately 0.97% (8.86 Mm^3/a) for Komati and 1.75% (16.02 Mm^3/a) for Usuthu whilst it dropped by 10.35% (94.95 Mm^3/a) and 13.56% (124.46 Mm^3/a) for Crocodile and Sabie-Sand respectively.
    - The decrease in the Inkomati-Usuthu WMA is 244.29 Mm^3/a which about 27%.
- Groundwater resource potential
    - The Komati is characterised by the highest groundwater potential of about 865.31 Mm^3/a followed by Usuthu and Crocodile at respective volumes of 357.79 Mm^3/a and 156.87 Mm^3/a whilst Sabie-Sand records the lowest at 93.83 Mm^3/a.
    - The sum of the individual catchment groundwater potential leads a 2 930.540 Mm^3/a of groundwater potential in the entire Inkomati-Usuthu WMA.
    - Compared to the year 2006 estimates by the GRA II:
        - Komati recorded the lowest groundwater potential decrease of about 78.72 Mm^3/a which is about 8% decrease,

    - Usuthu catchment exhibits a 40% (239.66 Mm^3/a) decrease,
    - Groundwater potential for Crocodile decreased by 77.83% (550.84 Mm^3/a),
    - Sabie-Sand decreased by 86.25% (588.52 Mm^3/a), and
    - The total decrease in groundwater resource potential across the entire Inkomati-Usuthu WMA is 1 456.74 Mm^3/a which is 49.71% decrease from the 2006 estimates.

- Groundwater budget
  - the outflows for Komati totalled 943.95 Mm^3/a whilst the inflow (groundwater recharge) is 908.86 Mm^3/a.
  - the outflows for Usuthu is 431.169 Mm^3/a with inflow of 397.81 Mm^3/a indicative that outflows outweigh the inflows.
  - Contrarily, inflows outweigh the outflows for Crocodile and Sabie-Sand because the inflows are respectively 318.01 Mm^3/a and 682.61 Mm^3/a compared to outflows of 101.12 Mm^3/a and 165.69 Mm^3/a for Crocodile and Sabie-Sand respectively.
  - The above notes are indicative that the groundwater budgets were imbalanced; the imbalances were:
    - 3.86% for Komati catchment,
    - 8.39% for Usuthu catchment,
    - 1.28% for Crocodile, and
    - 2.24% for Sabie-Sand.
  - The imbalance for Usuthu and Komati were attributed to the mountain block recharge whilst capture was attributed to the imbalance in the Crocodile and Sabie-Sand.
  - After accounting for the imbalances:
    - groundwater recharge constituted the highest percentages of the groundwater budgets amounting to 35.3% and 34.3% for Usuthu and Komati respectively; draft was apportioned respective percentage of 2.73% and 1.27% (Fig. 15).
    - groundwater recharge constituted the highest percentages of the groundwater budgets amounting to 44.65% and 43.27% for Crocodile and Sabie-Sand respectively; draft was apportioned respective percentage of 33.37% and 28.48% for Crocodile and Sabie-Sand respectively.

    - For Usuthu, the second biggest ration went to baseflow at 31.2% followed by groundwater potential at 29.3%.
    - for Komati baseflow and groundwater potential are 32.4% and 31.4% respectively.
    - The resultant change in storages are 0.64% and 1.37% for Komati and Usuthu, respectively.
    - For Crocodile, baseflow and groundwater potential are both at 11% whilst groundwater potential is 29.3% .
    - for Sabie-Sand, baseflow and groundwater potential are respectively 14.31% and 13.45%.
    - The resultant change in storages are 0.29% and 0.49% for Crocodile and Sabie Sand, respectively.
  - The results ultimately indicate that recharge and baseflow are the main controlling factors of the catchment wide groundwater balance for Komati and Usuthu. Contrarily, the catchment wide groundwater balance for Sabie-Sand and Crocodile is constrained by groundwater recharge, baseflow and draft.
- Catchment wide stress condition
  - The resultant stress index values are 0.03 and 0.08 for Komati and Usuthu respectively, indicative of unstressed condition; even if some areas might be stressed, that is not ubiquitous.
  - Crocodile and Usuthu are characterised by respective stress indices of 0.91 and 0.92 which is indicative of environmental water stress.
  - The catchment groundwater footprint (GF) for Komati was estimated as 5 169 km^2 (which is 59.96% of the total area) and that of Usuthu is 4 749 km^2 (which is 61.00% of the total area) resulting in GF/BA>1, indicative of unstressed condition (Table 4).
  - For Crocodile and Sabie-Sand, the GR are 9 483 Km^2 and 8 519 Km^2, which is 95% and 92% of the total areas for Komati and Sabie-Sand respectively resulting in GF/BA≅1, indicative of environmental water stress; consequently, groundwater resources are overused for both Crocodile and Sabie-Sand.

Contents

List of Figures

List of Tables

Glossary

Groundwater: Water found in the subsurface in the saturated zone.

Groundwater budget: The calculation of all inputs, outputs, and changes in the aquifer, including predictions for the future.

Catchment: Catchment in relation to watercourse or watercourses or part of a watercourse, means the area from which any rainfall will drain into the watercourses or part of a watercourse through surface flow to a common point or points.

Abstraction: The act of removing water from a groundwater resource.

Transpiration: The **s**ubsurface water uptake by plants.

Evapotranspiration: The loss of water from a land area through transpiration of plants and evaporation from the soil and surface water bodies an includes transpiration.

Draft: A combined groundwater consumptive use by both potential transpiration and human abstractions including also spring a wetland discharges.

Reserve: The quantity and quality of water required a) to satisfy basic human needs by securing a basic water supply, as prescribed under the Water Services Act, 1997 (Act No 108 of 1997), for people who are now or who will, in the reasonably near future and b) to protect aquatic ecosystems in order to secure ecologically sustainable development and use the relevant water resource.

Spring: A point where subsurface water emerges at surface, usually as a result of topographical, lithological or structural controls.

Wetland: The land which is transitionary between terrestrial and aquatic systems, where the water table is usually at or near the surface, or the land is periodically covered with shallow water, and which land in normal circumstances supports or would support vegetation typically adapted to life in saturated soil.

Groundwater recharge: The addition of water to the saturated zone, either by the downward percolation of precipitation or surface water and/or the lateral migration of groundwater from adjacent aquifers.

Baseflow: A sustained low flow in a river during dry or fair-weather conditions.

Storage coefficient: The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.

Drainage area: An area of land drained by a river and its tributaries (river system), including water found in the water table and surface run-off.

Recession curves: smoothed composite of the recessions of several observed hydrographs, drawn to represent the characteristic time graph of decreasing total runoff for a drainage area after passage of a peak flow.

Hydrograph: A graph of the flow in a stream over a period.

Recession coefficients or constants: The ratio of the discharge after a unit time step of some specific initial discharge to the specific initial discharge, provided both the discharges are along the same straight segment.

Groundwater storage change: The difference between groundwater inputs (e.g., recharge) and outputs (environmental flows and draft).

Groundwater stress: The ratio of groundwater withdrawal relative to its recharge rate over a given aquifer.

Groundwater footprint: The area required for sustainable use of groundwater for a region, such as a watershed, an aquifer, or a community.

Basic human needs: The prescribed minimum standard of water supply services necessary for the reliable supply of a sufficient quantity and quality of water to households, including informal households, to support life and personal hygiene.

Mountain-block recharge: Groundwater inflow to a lowland aquifer from an adjacent mountain block often referred to as a "hidden recharge".

Plantation: Forest planted for high volume production of wood, usually by planting one type of tree as a monoculture forest.

Hydraulic conductivity: The rate of flow under a unit hydraulic gradient through a unit cross-sectional area of aquifer.

Drought: The prolonged dry period in the natural climate cycle that can occur anywhere in the world.

Capture: the increased recharge but decreasing groundwater contribution to streamflow due to depleting groundwater storage.

1. Introduction

Vaux (2011) argued that evidence suggests that the most effective groundwater management institutions are those that are developed and managed locally. To this effect, within the past several decades, water resources planning, and management processes have increasingly involved the active participation of interested stakeholders at local level (Loucks et al. 2017). To that end, the South African National Water Act (NWA) (act 36 of 1998) promulgated the establishment of water institutions aimed at decentralising water resource governance. Chapter seven (7) of the NWA (act 36 of 1998) makes provision for the establishment of catchment management agencies (CMAs) whose mandate is to manage water resources in specified water management areas (WMAs). The WMAs are regional or local geographical areas within which water resource management takes place on premise that watersheds or river catchments are logical regions for water resources planning and management. There are nine water management areas in South Africa, which include Inkomati-Usuthu WMA, under the mandated authority of the Inkomati-Usuthu Water Management Agency (IUCMA). The mandate of the IUCMA is to perform water resource management at local level within the Inkomati-Usuthu Water Management Area (WMA). As promulgated by Section 80 of the NWA, the initial functions of the IUCMA include investigation and advise on the protection, use, development conservation, management, and control of the water resources in its WMA.

In global terms, water consumption has increased considerably since the beginning of the 20th century because of both population growth and increased water consumption thereby rapidly depleting the availability of water per capita (Jones 1997, Gleick 1996, Kundzewicz 2019). As a result, in nearly 80 nations, the demands exceed the supplies and this number is expected to grow even bigger by 2025 (Gleick, 1993, Shiklomanov (1998). South Africa is already part of the countries experiencing water scarcity where the increased demand already cannot be met in several locations and at a given assurance of supply. In 2016, with a population of 55.7 million, South Africa had only about 2 440 litres per day per person or 890 m^3 per person per year of water available which, based on the United Nations classification of water scarcity, might be deemed adequate; however, only 20-25% is reliably available (Le Maitre et al. 2019). In 2016, the population of south Africa was 55.7 million which, by June 2022, had grown by 4.9 million to 60.6 million (Stats SA 2011). This has correspondingly led to an increase in the water resource demand whereby approximately 98 percent of the predicted total surface water resources is already being used up. After allocating enough water in rivers for environmental flow requirements, international obligations (for transboundary WMAs) and strategic use (e.g., electricity generation) as promulgated by NWA (and existing protocol on shared water resources), the demand already exceeds the supply in half of the nine WMAs (Pott et al. 2009). This evokes worries about the potential water scarcity in the face of increasing population-driven water demands calling for technical measures of water conservation and augmentation which may include conjunctive use of surface water and groundwater (Kundzewicz 2019).

South Africa obtains its water supply from surface water equalling 77 percent of total use, groundwater at 9 percent of total use, and recycled water approximated at 14 percent of total use (Le Maitre et al. 2019). Groundwater is advantageous because its replenishment is not directly coupled to precipitation; therefore, it offers many opportunities to circumvent pressures on surface water resources (Onder and Yilmaz, 2005, Vaux 2011). More often than not, groundwater is relied upon when surface water resources are limited. As a result, the surface water allocations has at times exacerbated the overexploitation of groundwater, as groundwater has been used to compensate for any restrictions placed on surface water use (Speed 2013). Future efforts will need to look to couple conservation and sustainable development of water resources with development of untapped groundwater resources if its values are to be reaped sustainably. Given that groundwater is an integral component of the water supply, future increases in demand will present significant groundwater management challenges (Aral and Taylor 2011). Consequently, the South African National Water Resource Strategy 2 of 2013 considers groundwater resources as an important consideration for future planning and management of freshwater resources in the country.

As per Peter Drucker's (Drucker 2015) infamous say that one cannot manage and plan what they cannot measure, groundwater management requires a comprehensive situation assessment which is a prerequisite step for devising informed groundwater management. In South Africa, a pioneering study that resulted in quantitative estimates of groundwater resource availability was the 1995 national Groundwater Resource Assessment One (GRA I). The update of GRA I was instituted and completed in 2006 through the GRA II; consequently, the year 2022 marks a sixteen-year anniversary of the GRA II. In between 2006 and 2022, South Africa experienced a 2015/2016 drought that was termed one of the worst drought in the last 50 years (Monyela 2017). Additionally, groundwater reliance has grown drastically. For example, in response to the 2015/2016 drought, farmers, households, businesses and national governments adopted reactive solutions which involved extensive "panic" drilling of boreholes across the country. This increased use of groundwater inevitably continued after the said drought because installation of wells and the infrastructure for delivery of groundwater are a considerable investment. Consequently, it was imperative and indispensable that the groundwater resource accounting be updated. To that end, the aim of this study is to provide updated quantitative estimates of regional groundwater budgets of the Inkomati-Usuthu WMA.

2. Background

2.1. General

The Inkomati-Usuthu WMA is geographically wholly located within Mpumalanga Province, in the north-eastern part of south Africa. It has an approximate area of 36 256 km^2, with approximately 37 % of the land area being occupied by Nature Reserves (e.g., Kruger National Park, Sabie Sand Game Reserve Complex and numerous important Reserves under the management of the Mpumalanga Tourism and Parks Agency). The population within the Inkomati-Usuthu WMA is approximately 2 208 771 (Mukuyu et al. 2022).

The Inkomati-Usuthu WMA is characterised by four rivers individually draining Usuthu (7 915 km^2), Crocodile (10 446km^2), Komati (8 621 km^2) and Sabie-Sand (9 304 km^2) drainage catchments; consequently, the Inkomati-Usuthu WMA is made up of four river catchments (Fig. 2). The Usuthu and Crocodile catchments are drained by the Great Usuthu and Crocodile rivers respectively whilst the Sabie-Sand and Komati are drained by the Sabie and Komati rivers, respectively. The Komati rivers flow through the Kingdom of eSwatini before emerging back into south Africa and into the republic of Mozambique until eventually discharging into the Indian Ocean. Both the Sabie and Crocodile rivers flow into the Republic of Mozambique before ending up in the Indian ocean. Great Usuthu flows from the Republic of South Africa into the Kingdom of eSwatini and into the Republic of Mozambique. Consequently, the Inkomati-Usuthu WMA is transboundary wherein there is an existing water sharing treaty, under the Southern African Development Community (SADC) Protocol on Shared Watercourses, between the Republic of South Africa, Republic of Mozambique, and the Kingdom of eSwatini. Therefore, the management of water resources with the Inkomati-Usuthu WMA takes into consideration international obligations (i.e., prescribed flow into the republic of Mozambique and Kingdom of eSwatini) in terms of both quality and quantity of water flowing onto the two downstream countries.

Land use comprises timber plantation , agriculture, mining, industry. As of 2004, the estimated area of timber plantation in the WMA (including ESwatini) was 4000 km^2, which is 14 % of the total WMA area. The water resources within the WMA are used between irrigation, domestic industrial (e.g., paper and sugar mills), strategic uses (e.g., ESKOM, SASOL Secunda complex, and etcetera) and international obligations (Table *1*). population growth. This impact the assurance of supply of many water users especially the irrigation and the domestic water use which are often under water use restrictions.

Table 1: General water resource requirement and storage in the Inkomati-Usuthu WMA

Catchment ID	USUTHU	KOMATI	CROCODILE	SABIE-SAND
Key economic activities	Inter-basin transfer for supply to Vaal and Komati WMA. Strategic transfer for ESKOM, SASOL Secunda complex, third party users, timber plantation and irrigation.	Inter-basin transfer to supply strategic water for ESKOM, timber plantation and irrigation.	Timber plantation , irrigation and industry	Timber plantation , irrigation and eco-tourism
Water requirements	Domestic and strategic use, timber plantation	Domestic use, irrigation, eco-tourism and industry.	Domestic use, irrigation, paper and sugar mills	Domestic use, irrigation and eco-tourism
Water storage infrastructure	Heyshope, Jericho, Morgenstond and Westoe	Vygeboom and Nooitgedacht dams in upper Komati, Driekoppies dam in low Komati and Maguga dam in Swaziland.	Kwena dam, Witklip, Lomati, Klipkopjes, Primkop and Longmere	Inyaka dam, transfer pipeline from Sabie to Sand catchment, Da Gama

The topography directly influences the rainfall distribution in the WMA with most of the Rainfall falling in the mountainous areas in the western and central parts of the WMA. Most of the rainfall falls in the mountainous areas, in the western and central parts of the WMA, and varies from as high as 1445 mm/annum, in the escarpment and mountainous areas of the catchment, to as low as 470 mm in the lowveld region in the eastern and downstream portion of the catchment. Except for Usuthu, all the catchments are under surface water resource stress wherein the existing demand outweighs the supply (Fig. *1*). In general, the Inkomati-Usuthu WMA is 804 Mm^3/a in deficit with the biggest water user being irrigation followed by domestic and industrial and then forestry uses (Table *2*).

Table 2: Water uses by sector in the Inkomati-Usuthu WMA (Mukuyu et al. 2022).

Sector	Volume m^3	Percentage %
Agriculture: Irrigation	1010.5	50.5
Agriculture: Livestock watering	1.5	0.1
Forestry	419.5	20.9
Mining	19.6	1
Domestic and Industry	548.8	27.4
Schedule 1	1.6	0.1

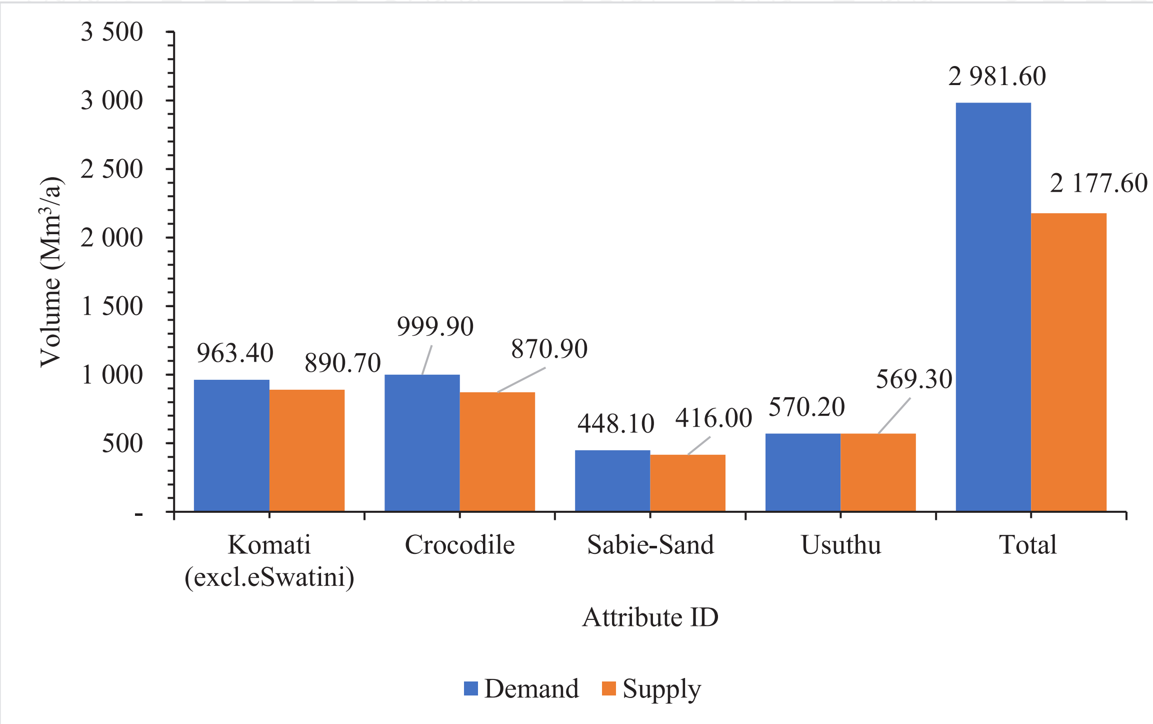


Fig. 1: Surface water balance for the Inkomati-Usuthu WMA

2.2. Geology and hydrogeology

Geologically, the Inkomati-Usuthu WMA is situated within the Kaapvaal Craton (Fig. *2*). The Kaapvaal Craton is intruded by rocks of stratified mafic and ultramafic, granitoid, carbonatite and alkali intrusion (Cawthorn et al 1981, Anhaeusser 2002). This includes the emplacement of the Bushveld Complex whose igneous activity begun with basalt–rhyolite bimodal volcanism, followed by the emplacement of the ultramafic–mafic Layered Suite, and finally the granitoid rocks of the granophyre granite suite (Litshedzani and Misra 2001). The bushveld igneous complex is found on the far western periphery of the WMA. The 'floor' of the Bushveld is intruded by a suite of generally mafic sills intruded into the strata of the Transvaal Supergroup. The Transvaal Supergroup defines a single and centripetally dipping structural basin containing (1) limestone and dolomite, (2) shale and interbedded shale carbonate, (3) siderite-rich banded iron-formation, and (4) iron oxide-rich banded iron-formation. The dolomite are not permeable (porosity <3%) (Button and Button 2015). Accompanying the main intrusion are numerous smaller intrusions that occur throughout the central parts of the Kaapvaal Craton as sills, dykes or plugs. Many of these intrusions appear to be of post-Transvaal but linked to the Bushveld event (Willemse 1959). They are interlayered or cross-cutting older volcano-sedimentary sequences, such as the Transvaal Supergroup (Cawthorn et al. 1981). Hydrogeologically, water is found along joints and faults, karst network and areas divided in compartments due to dolerite dykes where fracture yields can be more than 14 l/s. Strong springs yielding as high as 1157 l/s can be found, but those yielding >250 l/s are common (Groundwater dictionary).

The eastern side of the Komati and southeastern part of the crocodile, bordering eSwatini, are characterised by a northeast-trending Barberton Greenstone Belt. Also trending northwest, it also almost borders Usuthu sub-basin with the southwestern part of the eSwatini. It is a folded and metamorphosed volcano-sedimentary succession surrounded by intrusive granitoid rocks (Robb 1981). Mafic and ultramafic basalts predominate in the lower part of the sequence (Anhaeusser 2002). Both the lower and upper ultramafic-mafic part of the greenstone sequence hosts layered ultramafic to mafic intrusions. The layered bodies have undergone deformation involving folding and faulting and have been affected by low-grade regional metamorphism resulting from the intrusion of the Archaean granitic rocks surrounding the Barberton Greenstone Belt (Anhaeusser, 1986). Usuthu is bordered on the South to the northwest by sediments (dolerite, shale and sandstone) of the karoo supergroup whilst the Lebombo Group borders the Komati, Crocodile and Sabie-Sand with the Republic of Mozambique. Generally, The Lebombo Group consists of a thick sequence of basic and acid Karoo volcanics downfolded to the east along the eastern margin of the Karoo volcanic province (Anhaeusser, 1986). The stratigraphy of Lebombo include the basalts (interbedded rhyolites), rhyolites overlying the basalt (thick sequence of rhyolites which do not contain quartz phenocrysts). Dykes are present throughout the Lebombo, intruding the basalts. The consequent streams draining the Lebombo are largely controlled by the regional joint sets and by the bedding in the rhyolites (Cleverly 1979). Exiting the WMA into Mozambique, all the rivers (Usuthu, Komati, Crocodile and Sand) transect the Lebombo Group geology at right-angles to the strike. The rest of the WMA is characterised by the Archean basement comprising granitoids and gneisses which have low groundwater yields with yields as high as 16 l/s with transmissivity of 1400 m^2/d in structures.

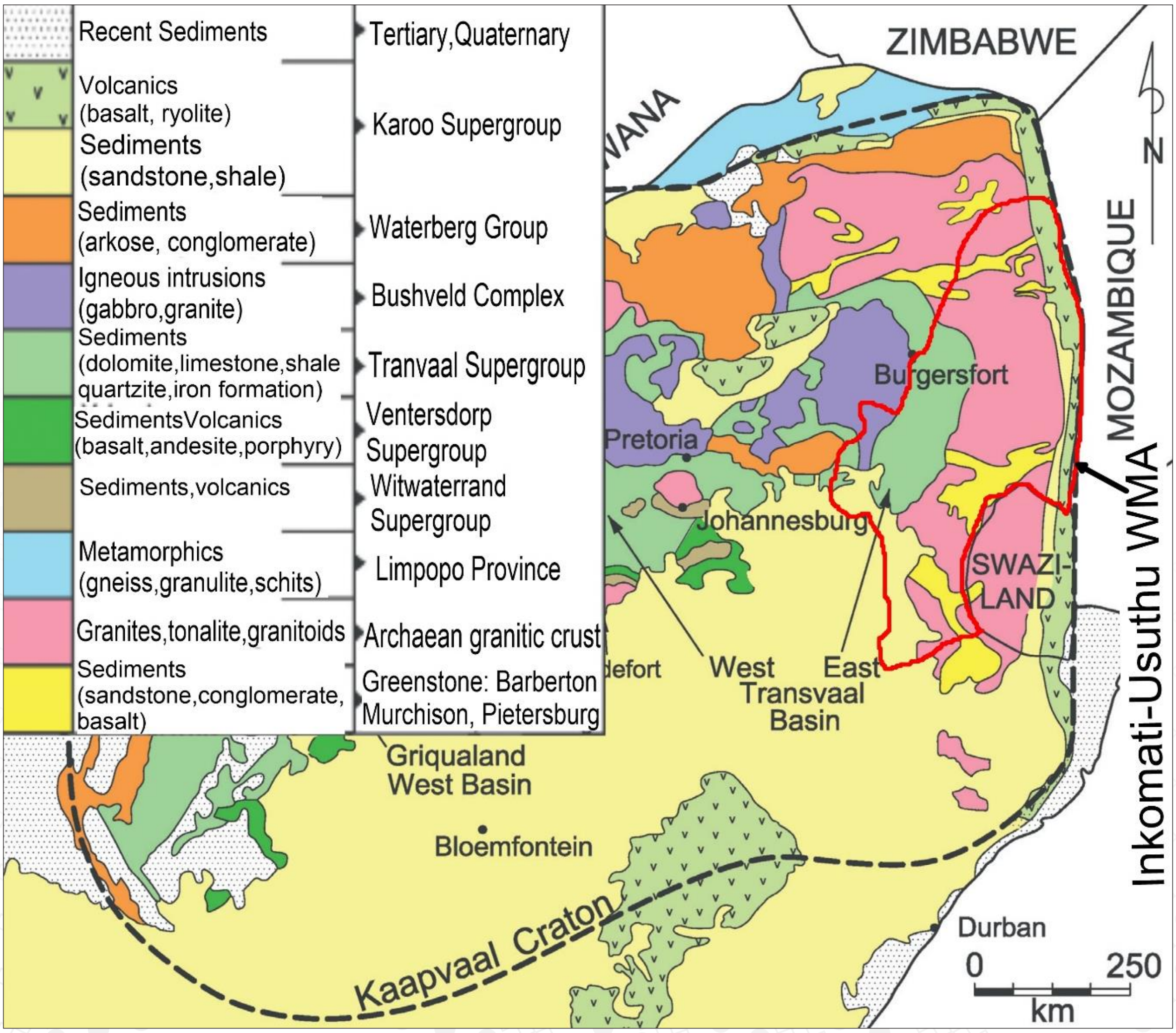
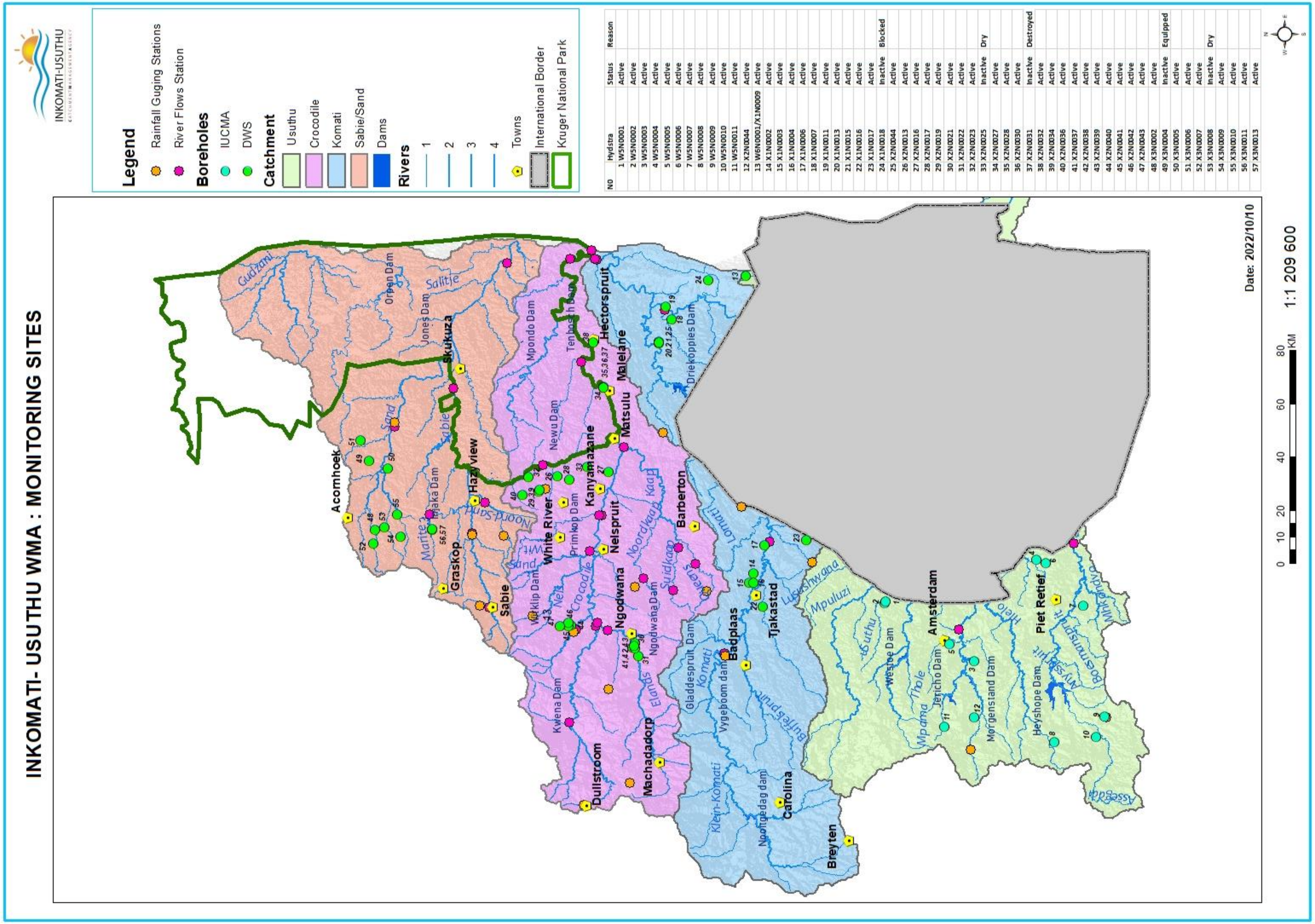


Fig. 2 Location of the Inkomati-Usuthu Water Management area (geological maps adapted from Button and Cawthorn 2015)

3. Method and material

According to Section 137 of the NWA, the Minister must establish national monitoring systems on water resources, which must provide for the collection of appropriate data and information necessary to assess, amongst others, the quantity of water in the various water resources (e.g., groundwater and surface water). Consequently, the IUCMA undertakes a routine groundwater monitoring within the Inkomati-Usuthu WMA using a hydrometeorological monitoring network comprising fifty-seven (57) geo-sites (boreholes), 31 river flow and 25 rainfall gauges (Fig. *3*). Groundwater monitoring is undertaken manually every month whilst both rainfall and stream flows are monitored using automated systems that telemetrically transmit data to custom relational databases housed at IUCMA head office. The data collected thus far is adequate to use in the calculation of groundwater balance parameters (i.e., baseflow form stream flow, recharge form streamflow, rainfall and groundwater levels, change in storage form water levels and streamflow)



NO	Hydstra	Status	Reason
1	W5N0001	Active	
2	W5N0002	Active	
3	W5N0003	Active	
4	W5N0004	Active	
5	W5N0005	Active	
6	W5N0006	Active	
7	W5N0007	Active	
8	W5N0008	Active	
9	W5N0009	Active	
10	W5N0010	Active	
11	W5N0011	Active	
12	X2N0044	Active	
13	W6N0001/X1N0009	Active	
14	X1N0002	Active	
15	X1N0003	Active	
16	X1N0004	Active	
17	X1N0006	Active	
18	X1N0007	Active	
19	X1N0011	Active	
20	X1N0013	Active	
21	X1N0015	Active	
22	X1N0016	Active	
23	X1N0017	Active	
24	X1N0018	Inactive	Blocked
25	X2N0044	Active	
26	X2N0013	Active	
27	X2N0016	Active	
28	X2N0017	Active	
29	X2N0019	Active	
30	X2N0021	Active	
31	X2N0022	Active	
32	X2N0023	Active	
33	X2N0025	Inactive	Dry
34	X2N0027	Active	
35	X2N0028	Active	
36	X2N0030	Active	
37	X2N0031	Inactive	Destroyed
38	X2N0032	Active	
39	X2N0034	Active	
40	X2N0036	Active	
41	X2N0037	Active	
42	X2N0038	Active	
43	X2N0039	Active	
44	X2N0040	Active	
45	X2N0041	Active	
46	X2N0042	Active	
47	X2N0043	Active	
48	X3N0002	Active	
49	X3N0004	Inactive	Equipped
50	X3N0005	Active	
51	X3N0006	Active	
52	X3N0007	Active	
53	X3N0008	Inactive	Dry
54	X3N0009	Active	
55	X3N0010	Active	
56	X3N0011	Active	
57	X3N0013	Active	

Fig. 3: Map showing hydrometeorological monitoring network within the Inkomati-Usuthu WMA

3.1. Groundwater budget

At predevelopment condition, a tight groundwater budget is presumably in an approximate steady state. In this case, groundwater outflow from the catchment primarily occurs as baseflow and transpiration by phreatophytic vegetation while inflow is predominantly through groundwater recharge. During development, abstraction is added to the outflow components thereby upsetting the natural balance. This upset must be balanced by an increase in recharge and/or decrease of baseflow or loss of storage (Bredehoeft 1982). In South Africa, the abstraction data is captured in the water use authorization & registration management system (WARMS). The database tends to record licensed groundwater pumping rates (as opposed to the actual rates verified in the field), disregarding groundwater users that are not registered (Allwright et al. 2013). This limitation is not only unique to South Africa; for example, in Denmark, Thorling et al. (2012) indicated that the water withdrawal data, registered in the Danish groundwater database Jupiter, are often inadequate because abstractions from irrigation wells and other private wells are often missing. Consequently, information on accurate abstraction volumes remains largely deceptive because actual groundwater withdrawal rates are seldom equal to the permitted rates.

Transpiration probably contributes the largest percentage of the outflow; however, its estimates are elusive compared to evapotranspiration (ET). However, evapotranspiration (ET) is a compound term describing a total water use from multiple sources; therefore, it would have to be disaggregated to correctly use in the groundwater budget. Both Tetzlaff et al. (2011) and Wang et al. (2013) reiterated that ET can hardly be measured directly at the catchment scales. To circumvent this challenge, both potential transpiration and groundwater use were lumped together as $draft$ (also known as blue groundwater footprint) which was solved as an unknown variable in the water balance equation. Chapter three of the NWA (act 36 of 1998) makes provision for environmental water entitlement through a concept of "ecological reserve" which often used to refer to the groundwater contribution to baseflow, spring discharges and wetland. The spring discharges and wetland contributions were taken as part of the draft. Consequently, the following water budget equation for the tight drainage catchment (closed system) was used (Genereux et al. 2004):

$$GW_r = draft + BF_a \pm \Delta S$$

where GW_r is a groundwater recharge (m^3/a), $draft$ is a combined groundwater abstraction by ET, groundwater users (boreholes), spring discharges and wetlands (m^3/a), BF_a is an actual groundwater contribution to stream flow (baseflow) (m^3/a), and ΔS is a dimensionless change in storage (m^3/a).

3.1.1. Groundwater Baseflow

For estimation of baseflow:

- The stream flow data from the river flow stations at the mouth of Upper Komati (Komati Upstream sub-system), and lower Komati (comprising lower Komati, Lomati, Komati West and Middle Komati sub-systems), where Komati River exits into Mozambique, were used for Komati.
- For Usuthu, the stream flow gauges at the mouths of all the subsystems (Assegai, Ngwepisi, Usuthu and Mpuluzi), before entry into eSwatini, were used.
- For both Sabie-Sand and crocodile, data from one gauging station each, located at the mouth of the catchments was used for baseflow estimations.

The streamflow data was subjected to a baseflow separation using the BFI+ 3.0 module (build 6) of HydroOffice 2010 software. In the software, a low pass filter recursive digital filter (RDF) method was used. Based on the assumption that the outflow from an aquifer is linearly proportional to its storage, the RDF based on Eckhardt (2005) digital filter, is expressed as follows:

$$BF_t = \frac{(1 - BFI_{max})\alpha BF_{t-1} + (1-\alpha)BFI_{max}Q_t}{1 - \alpha BFI_{max}}$$

where BF is a total baseflow (m^3/a), t is a time step number (years), Q is a total stream flow (m^3/a), α is a dimensionless recession constant, BFI is a baseflow index (ration of baseflow to total streamflow) and BFI_{max} is a maximum value of the BFI. Eckhardt (2005) suggested to set $BFI_{max} = 0.8$ for perennial streams with porous aquifers, $BFI_{max} = 0.5$ for ephemeral streams with porous aquifers, and $BFI_{max} = 0.25$ for perennial streams with hard rock aquifers.

Within the Inkomati-Usuthu WMA, the rivers draining the individual catchments are perennial whilst the ambient geology is predominantly crystalline (igneous and metamorphic). The groundwater occurs predominantly in the secondary porosity (fracturing and weathering); consequently, the B$BFI_{max} = 0.25$ was used. The Eckhardt filter was preferred as a conservative approach because it tends to reduce high BFI values. For example, no BFI value greater than 0.8 can be calculated because $BFI_{max} = 0.8$ (Eckhardt 2005).

3.1.2. Groundwater recharge

With minor modification from Healy and Cook (2002), the following equation was used to estimate groundwater recharge:

$$GW_r = AS\frac{\partial h}{\partial t}$$

where A is a catchment (drainage) area (m^2), S is a dimensionless storage coefficient of the catchment, ∂h is an average change in groundwater level (m) over change in time (∂t) (years). The approach assumed that the groundwater levels concurrently represent beds with water table conditions, and deep artesian (confined) aquifers. Long term change in groundwater levels were used; a six-year dataset (2016-2022) for Usuthu whilst an eleven years (2011-2022) dataset was used for the other three catchments (i.e., Komati, Sabie-Sand and Crocodile) respectively. Typically, collection of water-level data over one or more decades is required to compile a hydrologic record that can track trends with time (Isensee et al. 2022). However, for Usuthu, monitoring network only came into effect in 2016. Nevertheless, being more than five years and covering multiple hydrological years, the dataset is adequate to give indicative estimates, which must, however, be treated with caution.

3.1.3. Catchment storage coefficient and storage

The recession curves (specific part of discharge hydrograph after the precipitation event, where streamflow diminishes during a rainless or dry period) give a direct representation of channel storage effects and storage delay times of the catchment (Boughton and Askew 1968). This is because, during periods of streamflow decline (recession), streamflow in the river consists nearly entirely of groundwater discharge. Consequently, the characteristics of a recession can be determined by the recession coefficients or constants (related to time of storage or measure of the relative speed of the recession and amount of water released due to drainage) from the straight-line segments of natural logarithm of Q (discharge) versus t (time) using the following formulation (Hannula et al. 2003):

$$S = \frac{Q_1}{\alpha A Y_1}$$

where Q_1 is a streamflow rate at a specified time (m^3/a), α is a recession constant or depletion factor, and Y_1 is an average groundwater stage (m) at specified time (years). The recession constant, during a long-lasting dry period was estimated using the following single exponential equation (Toebes et al. 1969):

$$q_t = q_0 k^t$$

where q_0 is an initial discharge, q_t is a discharge at time t and k is a recession constant. Because it is usually negligible, the change in storage is often assumed to equal to zero; therefore, it is usually not included in groundwater budgets. However, this assumption could be nullified by the long-term changes in the hydrological states due to climate change and anthropogenic disturbances (Wang et al 2015). The groundwater storage change was estimated based on the published relationship between groundwater level fluctuation, storage coefficient and drainage area, based on the following formulation (Koïta et al. 2018):

$$\Delta S = AS\partial h$$

3.2. Groundwater stress and footprint

For the catchment wherein there is a mountain block recharge that leads to the groundwater balance equation imbalance by amplifying groundwater recharge, the groundwater potential were described in terms of stress condition using following formulation modified from Smakhtin et al. (2004):

$$GWSI = \frac{draft - 10\%}{(GW_r - \varepsilon) - BF_a}$$

where $GWSI$ is the groundwater stress index and ε is the water budget imbalance. The water budget imbalances have since been recognised in surface water budget equation; For example, Wang at al. (2015) presented the surface water balance equation for a drainage catchment with no net groundwater flow across its boundaries as $P - (1{,}0 - \alpha)\ ET - \alpha\ EO - Q - \Delta TWS = \varepsilon$. In instances where the baseflow is greater than groundwater recharge, the groundwater stress index was estimated using the following formulation:

$$GWSI = \frac{draft - 10\%}{(GW_r + \varepsilon) - BF_a}$$

The GWSI concept is appropriate for the purpose of this study because it was developed for use at the river catchment scale (Smakhtin et al. 2004). A 10% of draft was assigned as a guesstimate for spring and wetland contribution. If $GWSI$ is less than one, then groundwater stress is negligible; conversely, $GWSI$ equal or larger than one is a sign of unsustainable groundwater abstraction (Smakhtin et al. 2004). Smakhtin et al. (2004) provided an expanded guideline to assign the $GWSI$ with categories ranging from low to critical levels of stress as shown in Table 3. The limitations of the $GWSI$, as outlined by Hybel et al. (2016), are acknowledged.

Table 3 Groundwater stress condition guideline (Smakhtin et al. 2004)

STRESS INDEX	Interpretation
0 – 0.3	No water stress
0.3 – 0.6	Moderate env. water stress
0.6 – 1	Env. water stress
> 1	Env. water scarcity

Gleeson et al. (2012) defined groundwater footprint as the area required to sustain groundwater use, including groundwater-dependent ecosystem, in watersheds. Modified from Gleeson et al. (2012), the following formulation was used to estimate the catchment groundwater footprint:

$$GF = A\left(\frac{draft - 10\%}{(GW_r + \varepsilon)\ - BF_a}\right)$$

where GF (m^2) is a groundwater footprint, A is a catchment area and ε is a water budget. The ratio of groundwater footprint (GF) to catchment area (A) represents the groundwater stress indicator where $GF/BA > 1$ indicates unsustainable groundwater. In instances where the baseflow is greater than groundwater recharge, the groundwater footprint was alternatively estimated using the following formulation:

$$GF = A\left(\frac{draft}{(GW_r - \varepsilon)\ -(BF_a)}\right)$$

The GF can be used to estimate the groundwater stress index as GF/A where $GF/A > 1$ indicates where unsustainable groundwater consumption could affect groundwater potential and groundwater-dependent surface water and vice versa.

3.3. Groundwater resource potential

In the context of this study, the groundwater potential is defined as the ability of the subject catchment to supply groundwater of desired quantities. The catchment scale groundwater resource potential (GW_{RP}), was determined as follows.

$$GW_{RP} = (GW_r \pm \varepsilon) - [(draft - 10\%) + BHN]$$

The groundwater reserve is a compound term for ecological and basic human needs. The ecological reserve was estimated from stream flow baseflow separation, whilst the BHN component was calculated a product of the current population numbers and the minimum human water requirement. The 2011 population figures were obtained from Statistic South Africa (Stats SA), apportioned to the respective catchments and multiplied by twenty-five litres as promulgated by the South African Water Services Act (Act No. 108 of 1997).

It must be noted that the BHN essentially accounts for schedule one water use which entitles a person to take water for reasonable domestic purposes, watering of animals, peasant farming and firefighting, as defined in the Chapter 17 of the NWA (act 36 of 1998). The groundwater availability was calculated on assumption that 50% of respective catchment population (will) depend on groundwater resources for schedule one purposes. The imbalance was either added or subtracted to groundwater recharge to account for regional flow (mountain block or hidden recharge) or to ensure that environmental flow is not compromised.

4. Results

4.1. Groundwater baseflow

The results of baseflow estimations are shown in Fig. 4 to Fig. 7. The mean annual baseflow for the upper Komati was approximately 6.84 m^3/s whilst that of Lower Komati was 2.09 m^3/s. Based on the study of 20 selected catchments worldwide, Viviroli et al. (2003) found that the mountain contribution to annual river catchment discharge is about four times that of the lower reaches; consequently, the upper Komati contributed approximately three times that of the Lower Komati. This effectively indicates that there is high baseflow generation in the upper Komati compared to the lower Komati because of differing physiographic and abiotic factors.

In the Inkomati-Usuthu WMA, topography directly influences the rainfall distribution with most of it falling in the western and central parts. The western part (upper Komati) is characterised by elevations of up to two thousand metres above sea level which decreases to 900-100 mamsl range in the lower parts (lower Komati). Monthly rainfall is relatively higher in the upper Komati, averaging 96 mm per month compared to an average of 85 mm in the lower Komati (Fig. *6*). Steep topography of the upper Komati increase surface runoff resulting in the highest baseflow, and total streamflow compared to lower Komati. Rumsey et al. (2015) and Santhi et al. (2008) reiterated that baseflow yield is greater in high elevation areas where there is a greater percentage of rainfall and steeper slopes.

Just like many of the major river catchments of South Africa, Komati River has their headwaters in relatively high rainfall areas but pass-through areas with lower rainfall in the lower reaches. The consequence is that runoff generated in the headwaters is subject to transmission losses in the lower parts of the catchments (Huhges 2019). This is predominantly because, at the lower altitudes with relatively longer residence times, rivers are more exposed to the effects of intensive land use (Stoate et al. 2001). Land use and land cover (LULC), including effects of forest cover and agriculture, may have profound effects on baseflow generation with accompanying increase in groundwater demand impact in baseflow conditions and streamflow volume (Rumsey et al. 2015; Bosch et al. 2017).

An analysis of Fig. 9 revealed that there is almost equal distribution of groundwater abstraction boreholes (from WARMS) in both lower and upper Komati; however, lower Komati is predominantly characterised by a combination of high density irrigated agricultural land (mostly sugar cane farming) and timber plantation. Agricultural lands may decrease baseflow due to higher evapotranspiration rates, and higher abstractions. This may lead to increased ambient groundwater draft which may decrease groundwater contributions to streamflow (Rumsey et al. 2015). This is substantiated by Wittenberg (2003), who identified reduced baseflow resulting from abstraction for agricultural irrigation in northern Germany, Webber and Perry (2006) who demonstrated decline in baseflow due to over-abstraction of groundwater and Healy et al. (2007) who indicated that large-scale pumping for irrigation has reduced streamflow up to 30% in the High Plains Aquifer System in the United States.

The trendline for baseflow in the Komati and Usuthu were characterised by positive slopes, indicative of sustained groundwater contribution to baseflow. This can be attributable to unstressed groundwater situation wherein groundwater "recharge" far outweighs the outflows (i.e., draft). Recharge is parenthesised in this case because this includes mountain block recharge. Mountain-block recharge is groundwater inflow to a lowland aquifer from an adjacent mountain block often referred to as a "hidden recharge" (Feth 1964). Feth (1964) defined it as subsurface percolation of water from catchment-margin mountains directly into aquifers of the valley catchments.

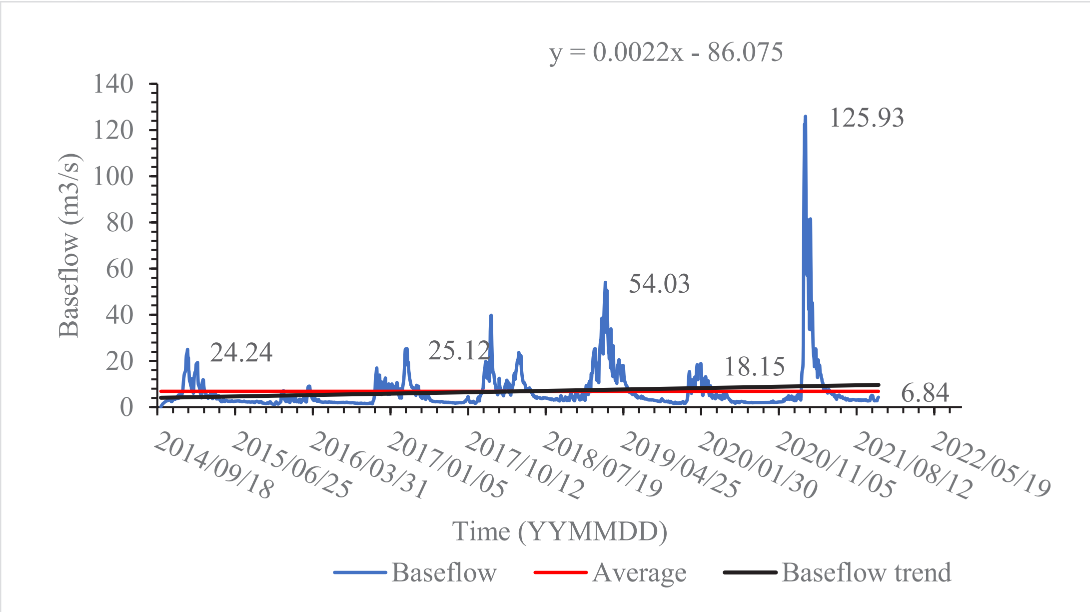


Fig. 4 Baseflow hydrograph for upper Komati

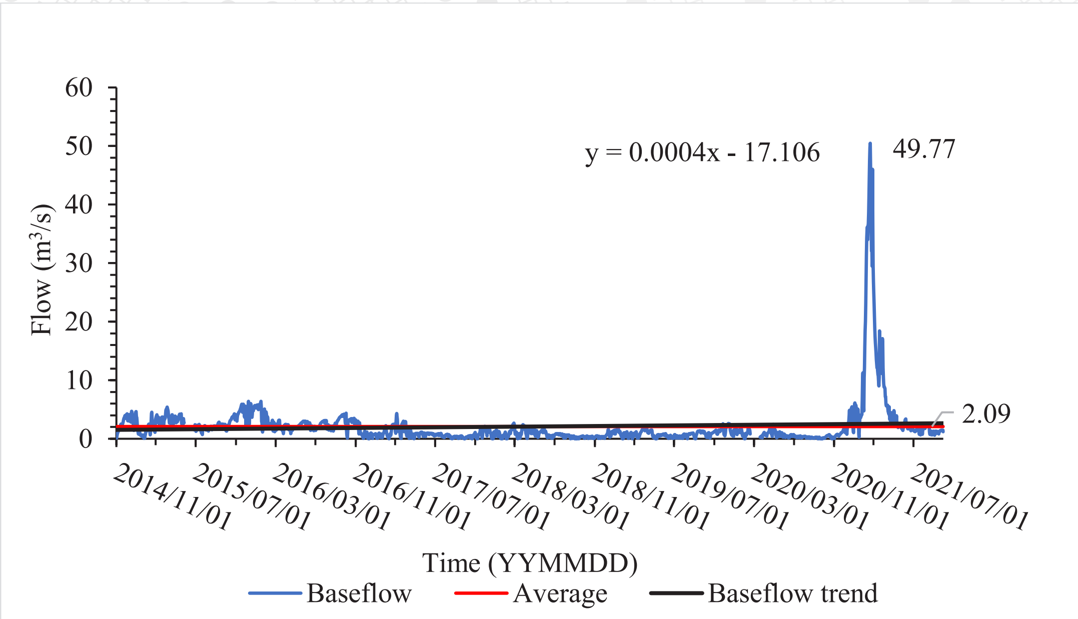


Fig. 5 Baseflow hydrograph for Lower Komati

The mean annual baseflow for Crocodile was about 9.05 m^3/s compared to the 6.19 m^3/s of the Sabie-Sand. The trend line for baseflow in the Sabie-Sand and Crocodile were characterised by negative slopes, indicative of decreasing baseflow. This is attributed to the baseflow capture characterised by the increased recharge but decreasing groundwater contribution to streamflow due to depleting groundwater storage brought about by increased or high groundwater draft. When abstraction occurs, changes in storage is initiated and, as abstraction continues and/or intensifies, the system tends to move toward a new dynamic equilibrium during which abstraction is largely compensated for by induced recharge and/or decreased discharge (Lohman et al. 1972).

High groundwater draft may potentially be due to increased groundwater withdrawals and/or increased transpirations. An analysis of Fig. 9 revealed that Crocodile and Sabie are characterised by much more timber plantation compared to Komati and Usuthu which, together with high density of registered groundwater boreholes, may lead to high draft which potentially outweighs the groundwater replenishment. When draft outweighs groundwater recharge, groundwater storage is depleted leading to baseflow capture and, consequently, decreased baseflow. What was also very conspicuous about the baseflow of crocodile catchment is the subdued nature soon after the years 2015/2016. In South Africa, starting in 2014, the Pacific Ocean was warmer than normal resulting in a strong 2015/2016 El Niño. This resulted in the 2015-2016 drought dubbed yet another severe drought, in the last 50 years, with little and variable rainfall (Monyela 2017).

In response to the 2015/2016 drought, farmers, households, businesses, and government adopted reactive solutions which involved extensive "panic" drilling of boreholes across the country. Consequently, during the 2015/2016 drought, there was less rainfall recharge and increased pumping from groundwater systems causing the observed decline of groundwater levels. This is over and above the high density of timber plantation that may lead to increased groundwater uptake. Groundwater level data indicated that most of the groundwater levels from Crocodile and Sabie-Sand never recovered after the drought and continue to progressively decline leading to the correspondingly decreasing baseflow as overserved.

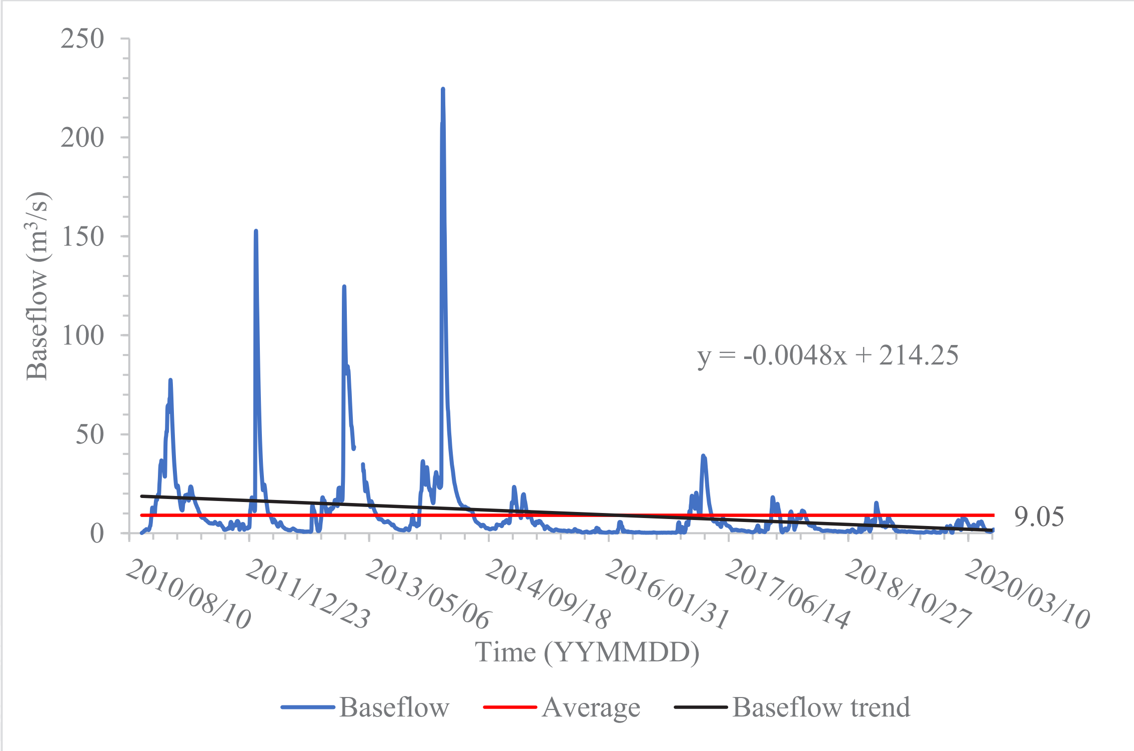


Fig. 6 A decadal baseflow hydrograph for Crocodile

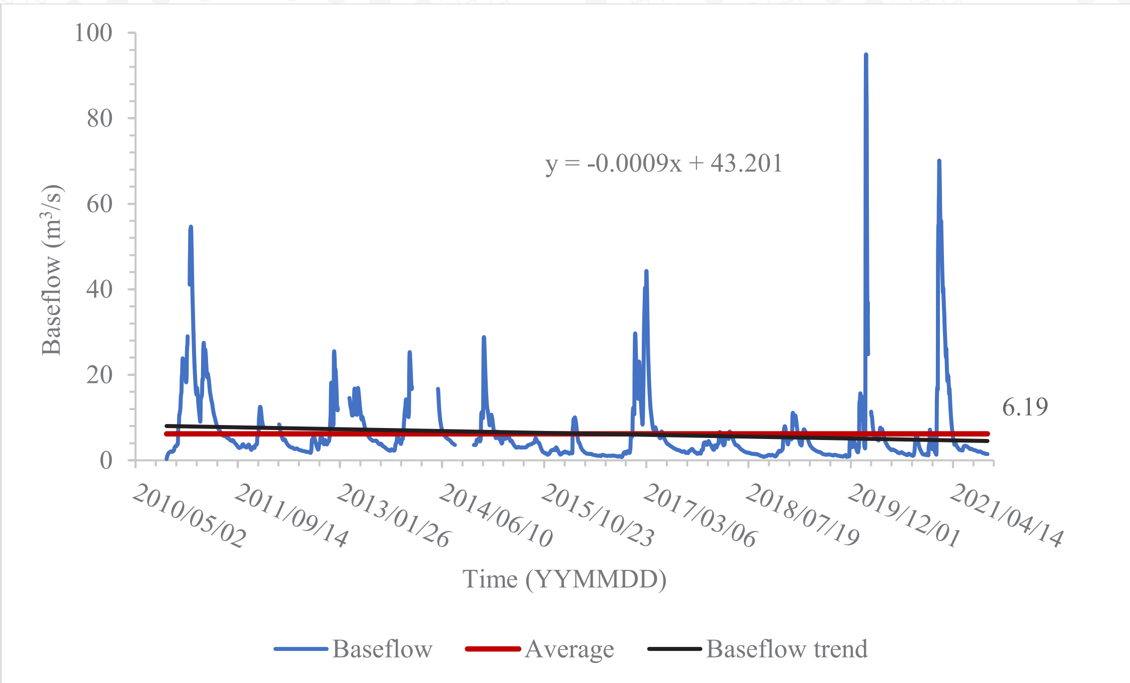


Fig. 7 A decadal baseflow hydrograph for Sabie-Sand

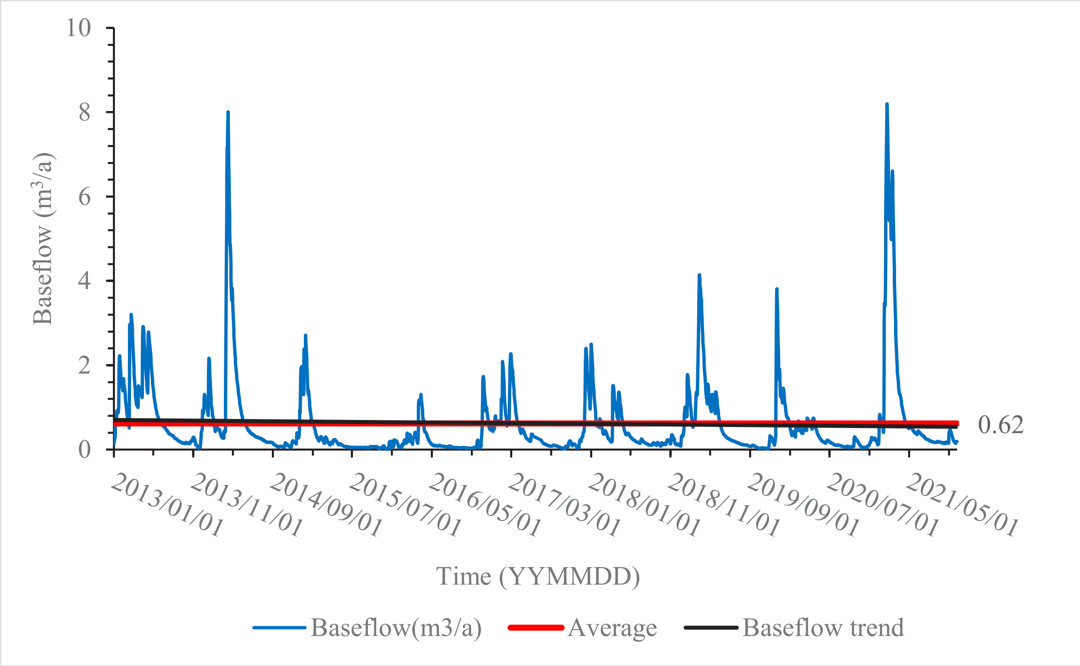


Fig. 8 Baseflow hydrograph for Usuthu

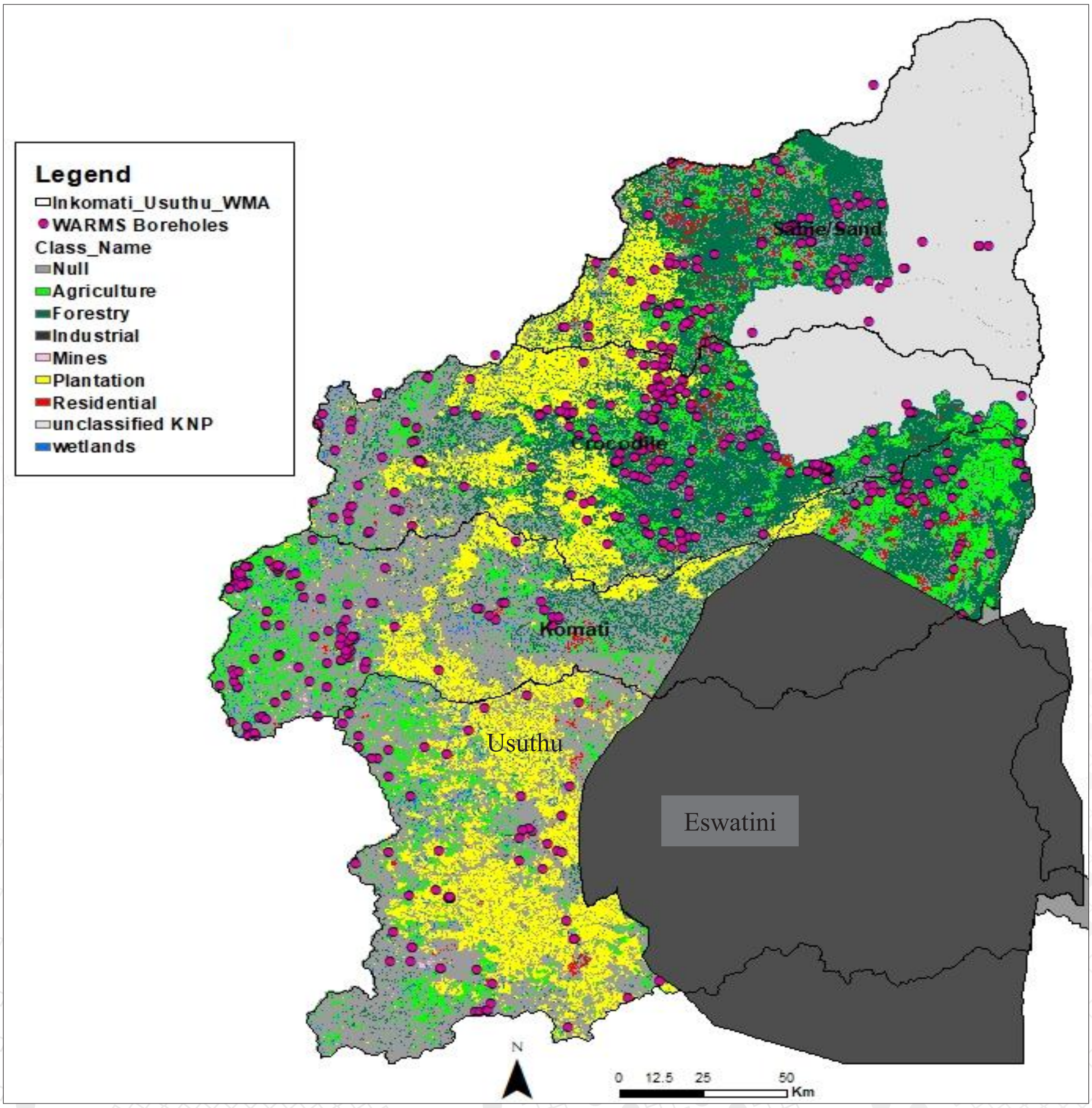


Fig. 9 A generalised land use map also showing the location of WAMRMS boreholes in the Usuthu and Komati catchments.

Average catchment wide baseflow estimates were originally 19 436 Mm^3/a and 8 527.17 Mm^3/a for Komati and Usuthu respectively (Fig. 10); however, these values were found to be higher than the groundwater recharge. This is not unprecedented because the results of GRA II also found that, in some catchments, baseflow was much higher than the volume of groundwater recharge. Such cases have also been reported in the High Plains Aquifer in North America (Costa Rica) and the Atlantic Coastal Plain (United States) (Genereux and Jordan 2006; Modica et al. 1998). This is related to the classical Toth (1963) theory of multiple-scale groundwater flow which indicates that groundwater flow can occur at multiple scales where shallow aquifers tend to force groundwater discharge to local rivers whilst deep aquifers develop regional flow. Regional flow is the deeper and longer-distance groundwater flow that transports water from one river catchment to another, and discharges far from the source (Schaller and

Fan 2008). Schaller and Fan (2008) indicated that if $BF_a{:}GW_r > 1$, the observed baseflow must include groundwater inflow from other catchments. In their study, Schaller and Fan (2008) found that the $BF_a{:}GW_r$ ratio ranged from 0.03 to 8.92, with half (50.4%) of the catchments above one (importers). Consequently, if deeper, long-distance groundwater flow is a significant part of a river catchment's water budget, the current approach may overestimate river flow. To circumvent this overestimate, the GRA II adjusted recharge upward to match the baseflow. In this study, a correction factor *(q_n)* denoting the net flux of water entering the catchments other than groundwater recharge, was applied to baseflow volume as follows: $q_n = (BF \pm \Delta S) - GW_r$ and actual baseflow (BF_a) was eventually calculated as $BF - q_n$. In this case, the only regional flow that will be included in the water budget is that which originates from within the confines of the two catchments (Usuthu and Komati), such as mountain front recharge.

After applying the correction factor, baseflow for Komati was 891.32 Mm^3/a. For Usuthu catchment, baseflow was 381.13 Mm^3/a whilst that of Crocodile and Sabie-Sand were 170.33 Mm^3/a and 107.57 Mm^3/a respectively. Of the four catchments, Crocodile and Sabie-Sand have more timber plantation (Fig. 9). Increase in forest area increases evapotranspiration leading to reduced groundwater recharge and, subsequently, reduced baseflow due to capture. Hamilton (2008) reiterated that, where there is heavy water-using species plantations, low flows are usually diminished.

The area of commercial timber plantations in South Africa is estimated at 1.5 million ha (comprising 57% pine, 35% eucalypts and 8% wattle), covering about 1.2% of South Africa (Scott et al. 1998). In the Inkomati-Usuthu WMA, rainfall varies from as high as 1445 mm/a in the escarpment and mountainous areas of the catchment to as low as 470 mm in the middle and lower reaches. This is by far more than the countrywide mean annual rainfall of 450 mm/year. Consequently, most (40%) of the commercial timber plantations are spatially concentrated here with the highest concentration of 7.2% of land area leading to the largest reductions in stream flows of almost 10% of total flow and 18% of low flows (Scott et al. 1998). This is not unique; reference is made to Scott et al. (2005) who provided much broader information on the topic whilst other evidence is provided in the eucalypt dilemma publication by Roberts (1988).

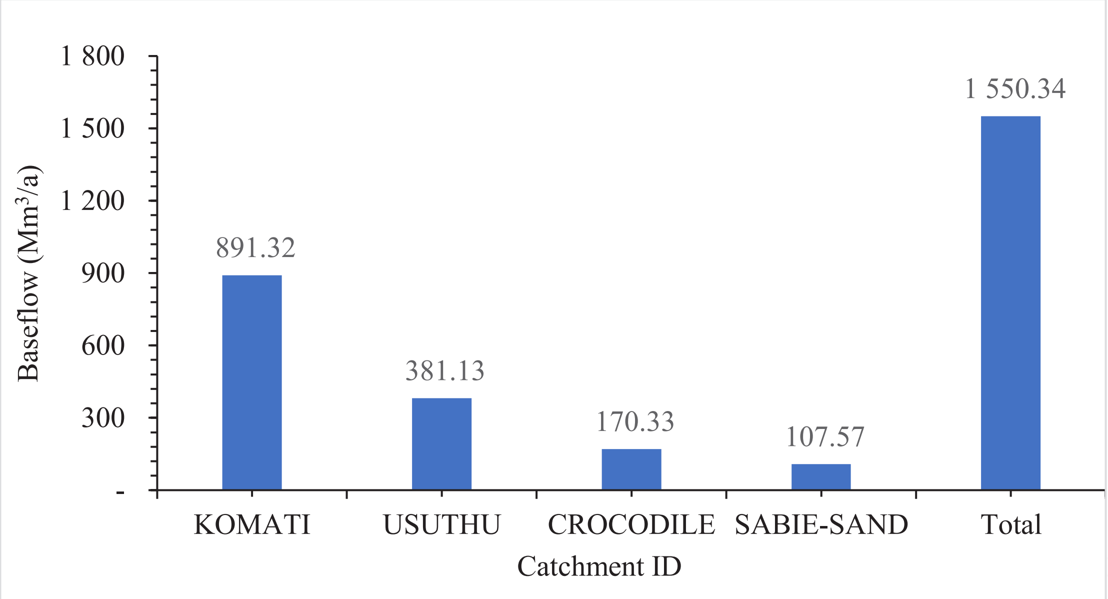


Fig. 10: Annual baseflow for the four catchments in the Inkomati-Usuthu WMA

4.2. Catchment storage coefficient

The recession curves for all the four catchments are presented in Fig. 12 to Fig. 14 on which the recession constants (slope of the exponential trendlines) are shown. By way of background, the largest recession constants represent the rapid depletion of the flow channels with the highest hydraulic conductivities whilst the lowest are representative of slow depletion of the flow network with low hydraulic conductivity (Amit et al. 2002). The highest flow is expected in the lower Komati with an average recession constant of 0.11 day^{-1} compared to the upper Komati with the recession constant of 0.01 day^{-1} (Table *4*). This conforms to the Welch and Allen (2014) conceptual model for hydraulic conductivity heterogeneity in crystalline bedrock mountainous environments.

Permeability of the porous medium is responsible for discharge rate and its capacity is responsible for perennial or seasonal behaviour of the stream (Vashisht and Bam 2013). In fact, the numerical model of Darcy's flow equation confirms that baseflow represents the depletion of the low hydraulic conductivity (Eisenlohr et al. 1997). The maximum volume of water in lesser time will be stored in the portion with highest permeability leading to earlier depletion in comparison to catchment portions with low permeability. To this effect, lower Komati is potentially characterised by higher hydraulic conductivities with rapid and short-lived baseflow contributions. Contrarily, the upper Komati is characterised by lower hydraulic conductivities and slow depletion of groundwater into the ambient stream flow. Consequently, upper Komati potentially sustains most of the stream flow in the Komati catchment.

On average, Komati was characterised by a recession constant of 0.08 day^{-}compared to the 0.02 day^{-1} of Crocodile and Usuthu whilst Sabie-Sand was characterised by the least recession constant of

0.01 day^{-1}. Compared to Komati, Usuthu was characterised by relatively lower recession constant, representative of slow depletion of the flow network with low hydraulic conductivity. Based on the recession constant values, Komati is characterised by the highest hydraulic conductivities with rapid depletion of the flow channels whilst Sabie-Sand is characterised by lowest hydraulic conductivities with delayed depletion of the flow channels.

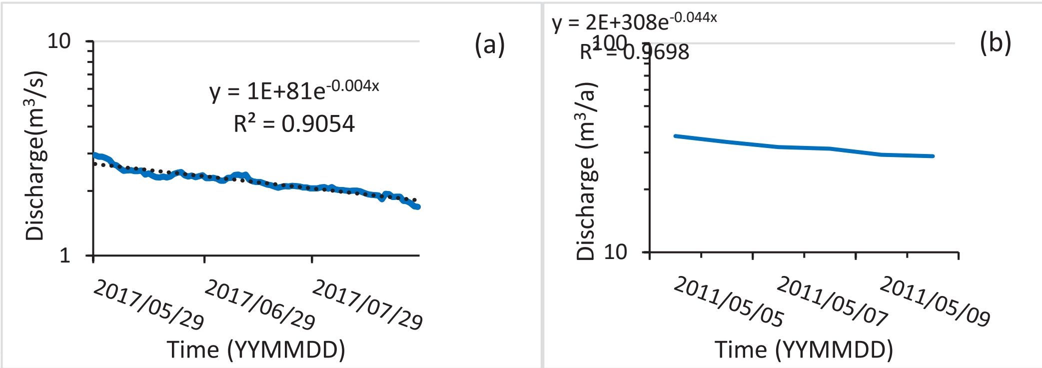


Fig. 11 Approximation of the recession curve for a) upper Komati and b) lower Komati

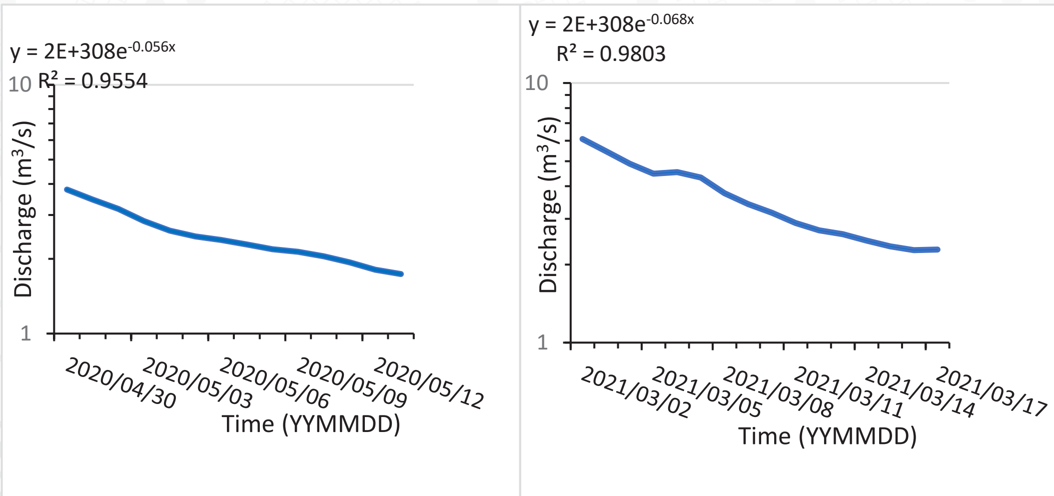


Fig. 12 Approximation of the recession curves for Usuthu catchment

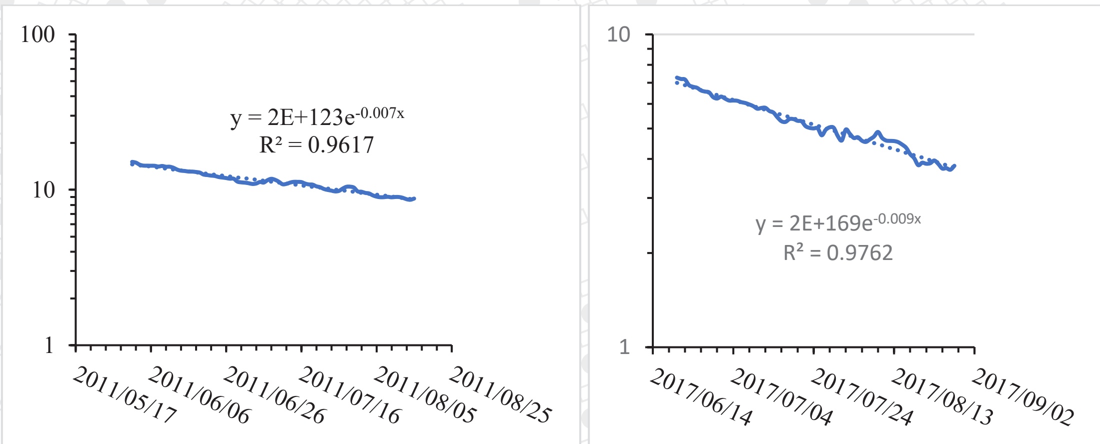


Fig. 13 Approximation of the recession curves for Crocodile catchment

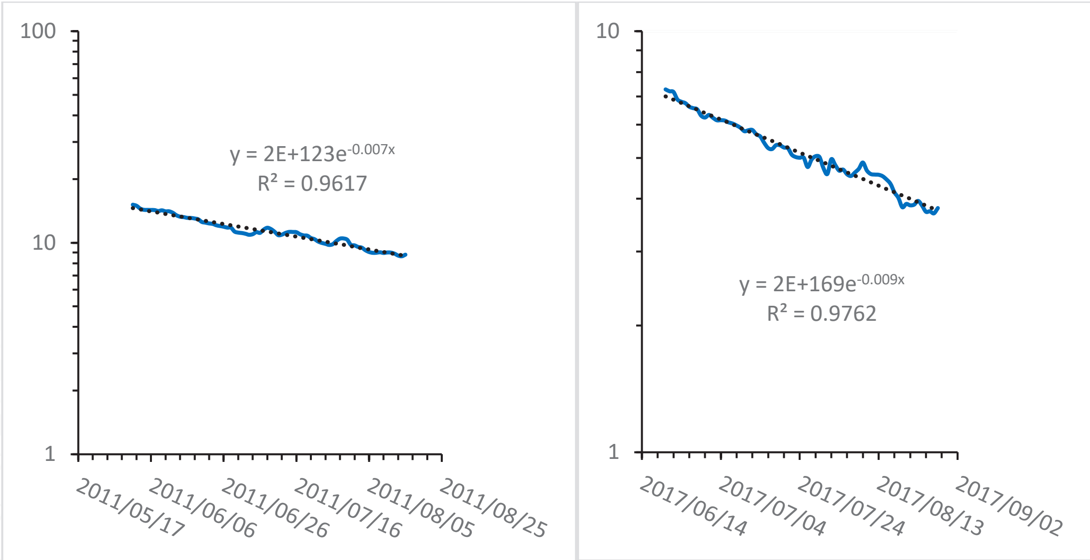


Fig. 14 Approximation of the recession curves for Sabie catchment

The recession constants were used to estimate the catchment storage coefficient and the estimates are shown in Table 4. By way of background, the storage coefficient of most confined aquifers ranges from about 10^{-5} to 10^{-3} whilst that of most unconfined aquifers ranges between 0.1 and 0.3 and averages about 0.2 (Lohman 1972, Freeze and Cherry 1979). The average storage coefficient of Komati was estimated as 0.003 whilst that for Usuthu was 0.008 compared to 0.0064 and 0.0023 for Crocodile and Sabie-Sand respectively (Table 4). The storage coefficients for all the four catchments imply that the prominent source of groundwater discharge is from the regional flow systems (i.e., from deep aquifers) that tend to transport water and discharged it far from its source. This would presumably be from high rainfall mountainous areas leading to mountain front recharge.

Table 4 Summary of averaged parameters for recharge estimates in different sub-systems of the Komati and Usuthu catchments

Sub-systems	GW Stage (m)	Q (m^3/s)	ʎ (day-1)	S
		Komati		
Lower Komati	0.52	3.36	0.14	0.007
Lomati	0.9	1.67	0.1	0.002
Komati West	0.65	3.17	0.08	0.004
Upper Komati	0.85	2.67	0.01	0.008
Average	**0.73**	**2.72**	**0.08**	**0.005**
		Usuthu		
Assegai	0.84	1.21	0.03	0.0026
Ngwepisi	1.5	0.64	0.03	0.0018
Usuthu	1.19	0.13	0.02	0.0012

Mpuluzi	1.19	0.82	0.01	0.0047
Average	**1.18**	**0.7**	**0.02**	**0.0026**
Crocodile				
Average	0.19	2.4	0.02	0.0064
Sabie-Sand				
Average	1.84	5.39	0.01	0.0023

4.3. Groundwater storage and draft

During the 2015-2016 drought, rainfall declined to 585.8 mm leading to a considerable decrease of 426 mm rainfall from average. Long-term drought, which virtually always result in reduced groundwater recharge, may be viewed as a natural stress on groundwater systems which may lead to decline in groundwater storage and discharge to surface water bodies (e.g., streams, wetlands and springs). During the 2015/2016 drought, the groundwater levels across the four catchments (i.e., Usuthu, Komati, Crocodile and Sabie-Sand) progressively declined indicative that the meteorological droughts propagated to the groundwater recharge (Fig. 16 to Fig. 18).

Since monitoring data for the Usuthu catchment boreholes started after the 2015/2016 drought, groundwater levels are currently in the increasing trajectory in response to increased rainfall after the drought stress (Fig. 15). For Komati, Crocodile and Sabie-Sand, groundwater level monitoring started about five years before the drought. Groundwater levels in Komati are recovering from the drought stress; consequently, on average, Usuthu and Komati catchments experience positive change in groundwater levels corresponding to an approximated change in storage of 16.68 Mm^3/a and 17.54 Mm^3/a respectively (Fig. 19). This contrasts with both Crocodile and Sabie-Sand where, way after the 2016 drought, groundwater levels continue to progressively decrease leading to negative groundwater storage change of - 4.41 Mm^3/a and -3.65 Mm^3/a respectively.

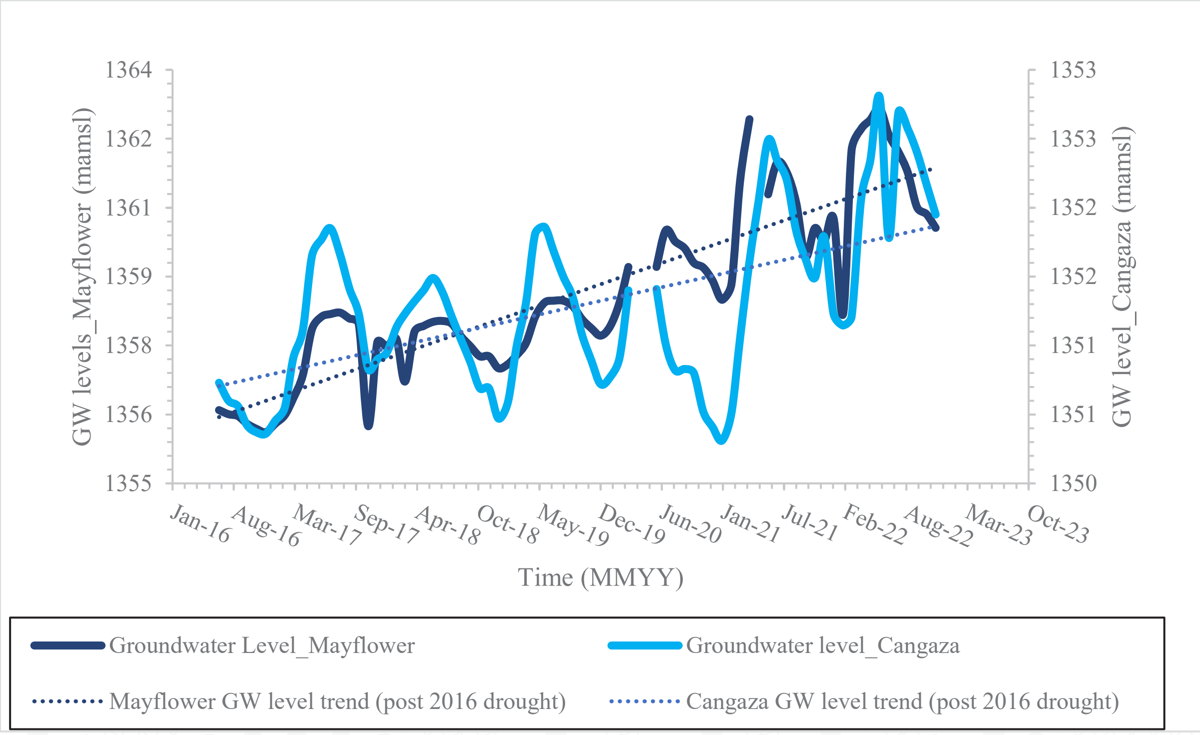


Fig. 15: A composite hydrograph of groundwater levels in the Usuthu (Mpuluzi and Ngwepisi Sub-systems)

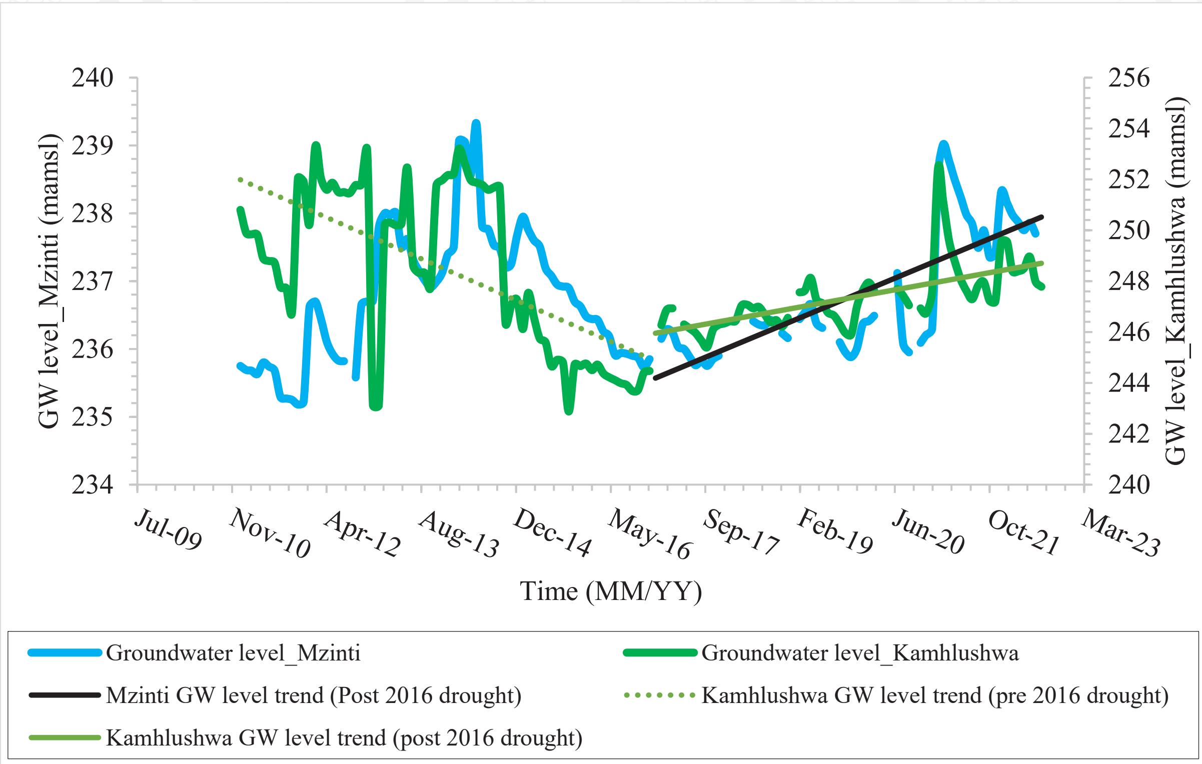


Fig. 16: A composite hydrograph of groundwater levels in the lower Komati (Komati West and Lomati Sub-systems)

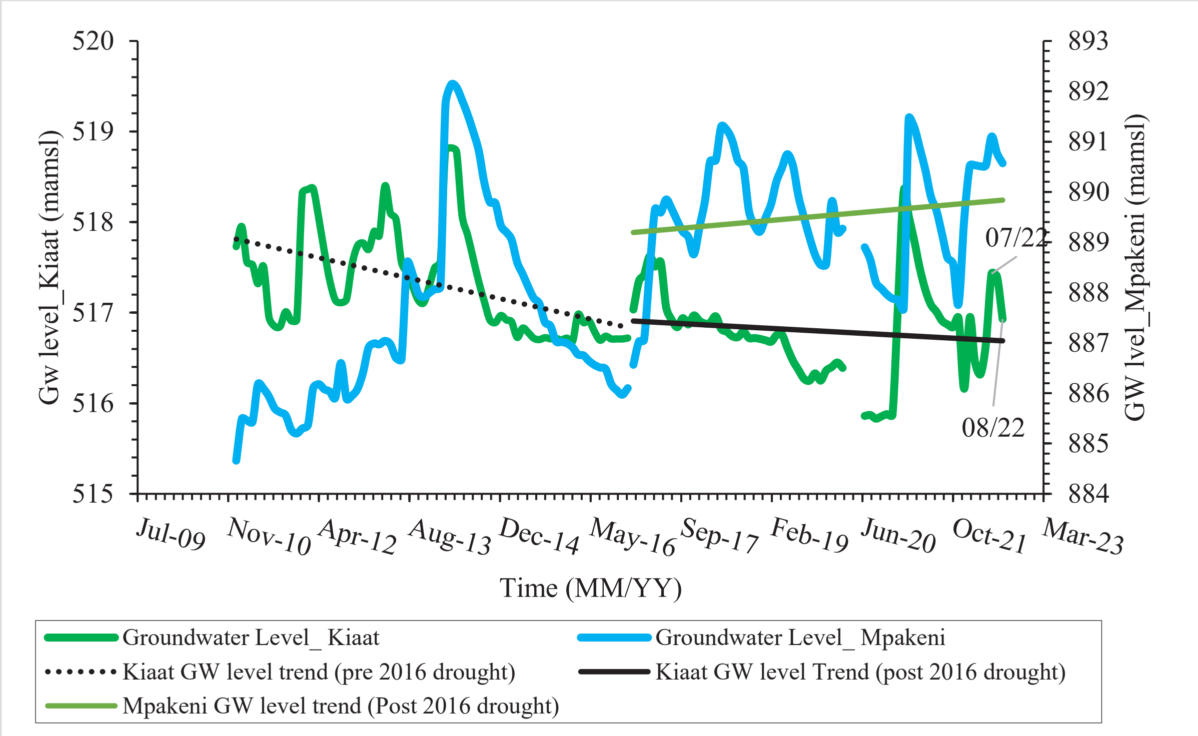


Fig. 17: A composite hydrograph of groundwater levels in the Crocodile (Middle Crocodile Sub-System)

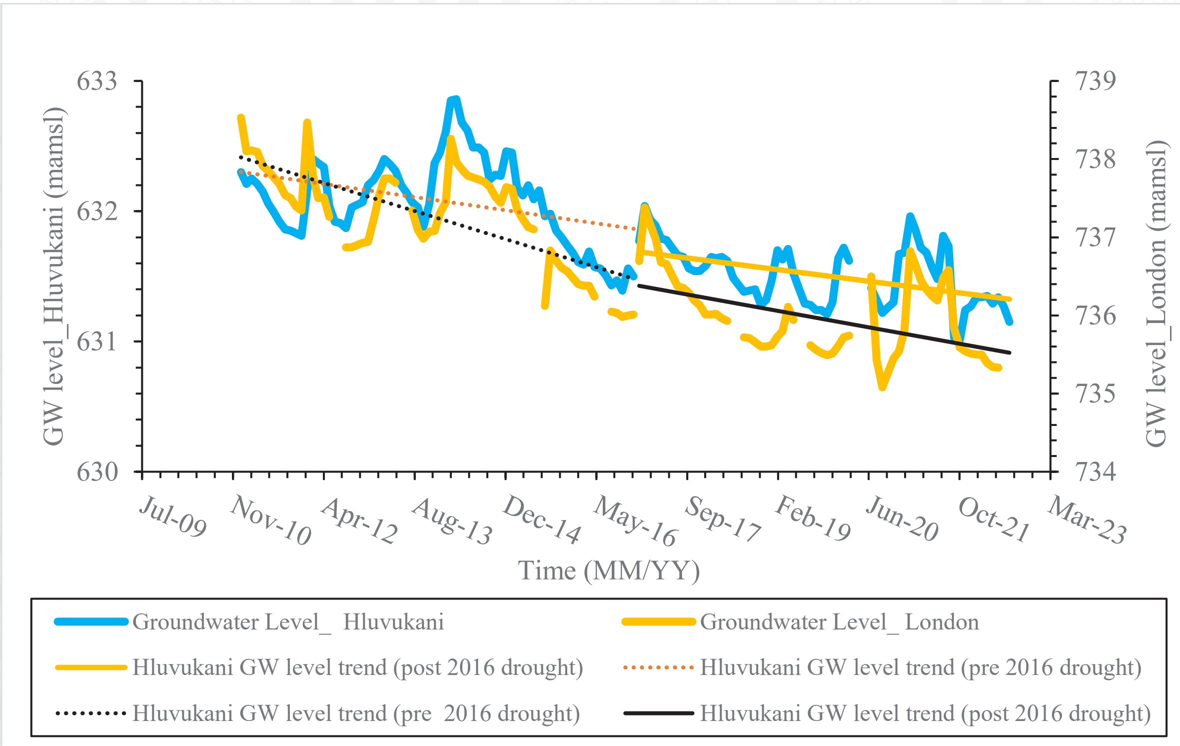


Fig. 18: A composite hydrograph of groundwater levels in the Sabie-Sand (Sand River Sub-System)

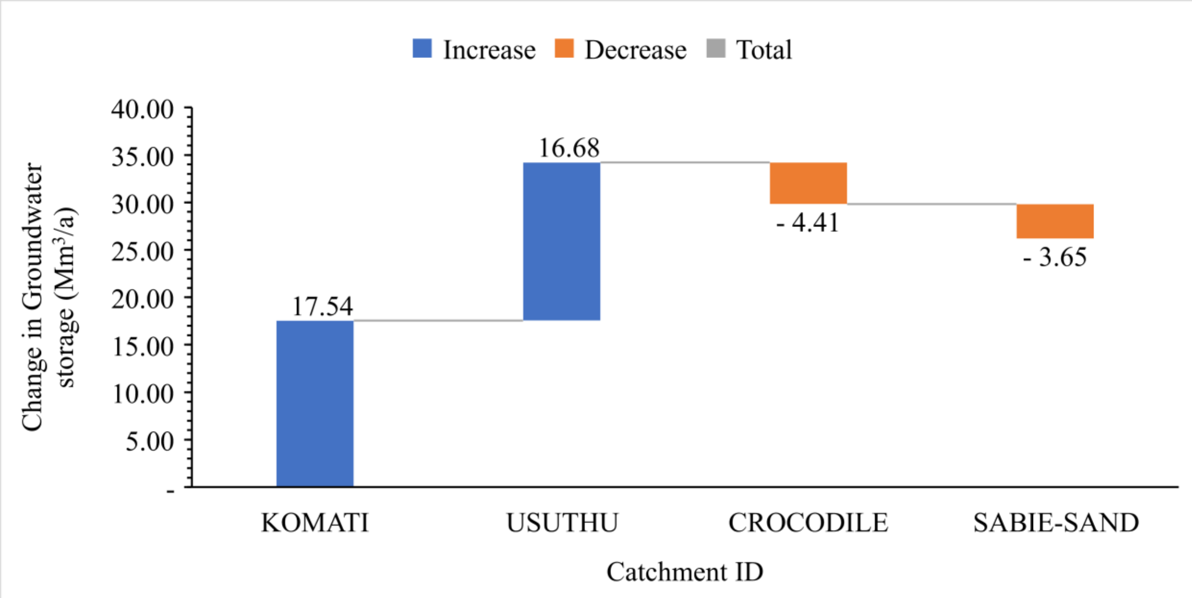


Fig. 19 Change in groundwater level for Komati and the resultant groundwater change in storage for both Usuthu and Komati

The results for draft calculations are presented in Fig. 20 against with the following key notes made of the groundwater draft.

- At 516.69 Mm^3/a, the draft for Crocodile was the highest followed by that of Sabie-Sand at 214 Mm^3/a.
- At (35.09 Mm^3/a), that of Komati catchment is about 1.73 mm^3/a more compared to Usuthu,
- Compared to the WARMS data, the draft is 32.31 Mm^3/a more for Usuthu and 15.44 Mm^3/a more for Komati whilst that of Crocodile and Sabie-Sand are 513.89 Mm^3/a and 211.36 Mm^3/a.

The differences between draft and WARMS data represent the volumes attributable to sinks other than licenced abstraction, notably transpiration magnitudes. This is positively coupled to land use where timber plantations (pines, eucalypts and wattle) are more prevalent in the Crocodile followed by Sabie-sand, Komati and Usuthu; in that order (Fig. 9). These estimates should be taken with caution because WARMS only includes registered abstraction whilst the draft also includes unauthorised groundwater extraction. Nevertheless, the numbers give a baseline indication that transpiration contributes the biggest groundwater use in the two catchments especially eucalypts. These tree species grow more rapidly than other species which is associated with greater consumption of water (Teketay 2000). From groundwater perspective, they functions as deep-rooted “water pumps” much like the effect of pumped wells (Winter et al. 1998).

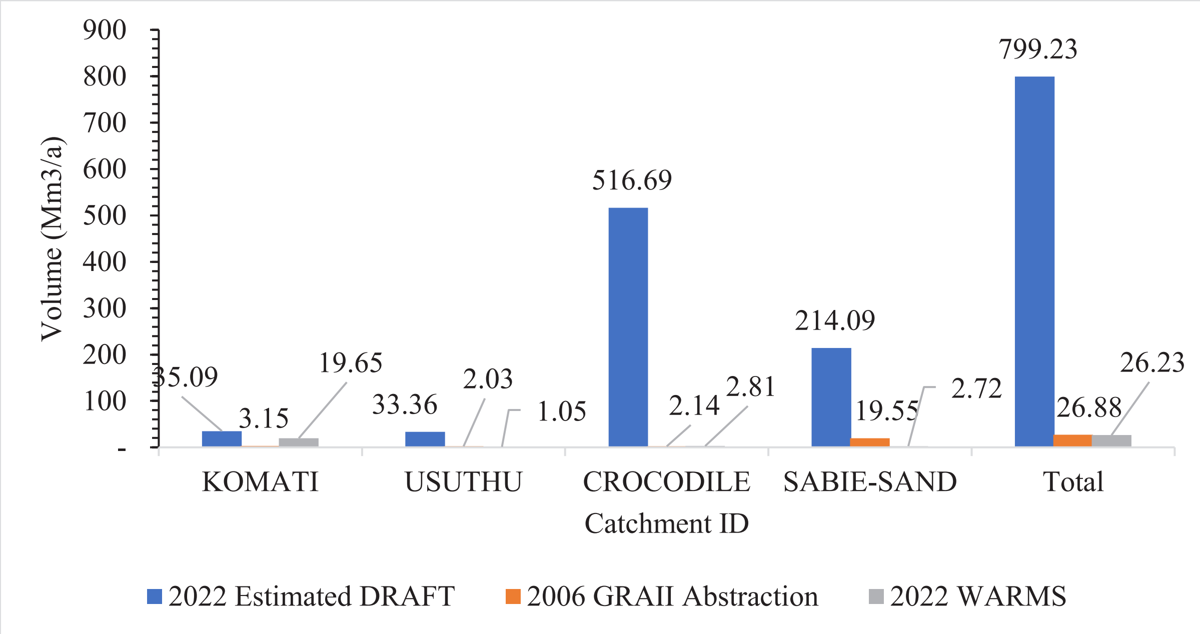


Fig. 20 Draft estimates compared to the abstraction data from the 2006 GRA II study and the 2022 WARMS.

4.4. Groundwater Recharge

Groundwater recharge percentages are presented in Table 5 whilst the volumes are presented in Fig. 21 against which the following key notes are made:

- groundwater recharge for Komati ranged between 2.11% and 8.86% and averaged 4.86%
- For Usuthu, groundwater recharge ranged between 1.17% and 5.83% with an average of 3.5% (Table 5).
- Groundwater recharge for Crocodile and Sabie-Sand averaged 6.62% and 3.50% respectively.
- Komati received the highest groundwater replenishment of about 909 Mm^3/a compared to the 398 Mm^3/a of Usuthu.
- Sabie-Sand and Crocodile recharge were respectively 325.30 Mm^3/a and 691.43 Mm^3/a.
- Compared to the GRA II estimate,
    - groundwater recharge dropped by approximately 8.86 Mm^3/a for Komati and 16.02 Mm^3/a for Usuthu which is 1% and 1.75% respectively.
    - groundwater recharge dropped by 10% (94.95 Mm^3/a) and 14% (124.46 Mm^3/a) for Crocodile and Sabie-Sand respectively.
    - The decrease in the Inkomati-Usuthu WMA was 244.29 Mm^3/a which is approximately 27% decrease.

The immediate potential culprits for groundwater declines are rainfall and widespread commercial forest plantation through evapotranspiration (i.e., unsaturated zone transpiration, canopy and litter interception). A 48-year cumulative rainfall data revealed that rainfall is decreasing in the Inkomati-

Usuthu WMA with the highest decrease rate being in the Usuthu (at 3.92 mm/a) followed by Crocodile at 2.4 mm/a, Sabie-Sand (at 1.47 mm/a) and Komati (at 0.86 mm/a) (Fig. 22). This is indicative of a decreasing rainfall which leads to decreased amount of rainfall available to recharge the groundwater. The highest decreasing rate if rainfall is Usuthu followed by Crocodile, Sabie-Sand and then Komati.

Canopy and litter interception contribute a significant amount of the water evaporated in a forest water balance, averaging 30% (21% canopy and 9% litter) of gross precipitation in South Africa (Bulcock and Jewitt 2012). This has been attributed to the observed 10% reductions of total stream flow and 18% reduction of low flows. Between 2016 and 2018, the fifth edition of the State of the Forests Report (2018) established an increase of 1% in afforested area in the Mpumalanga. Most plantations occur at elevations between 1000 and 2000 m in the areas receiving more than about 850 mm of rainfall annually. The afforested land occurs predominantly in these high rainfall regions of the country which effectively means increase interception and correspondingly decreased rainfall for groundwater storage (Bulcock and Jewitt 2012).

Table 5 Average recharge estimates for Komati and Usuthu catchments

Sub-systems	Re (%)
Komati	
Usuthu	3.5
Komati	4.86
Crocodile	2.11
Upper Komati	8.44
Average	**4.86**
Usuthu	
Assegai	1.40
Ngwepisi	1.17
Usuthu	5.83
Mpuluzi	5.60
Average	**3.50**
Sabie-Sand	3.50
Crocodile	6.62

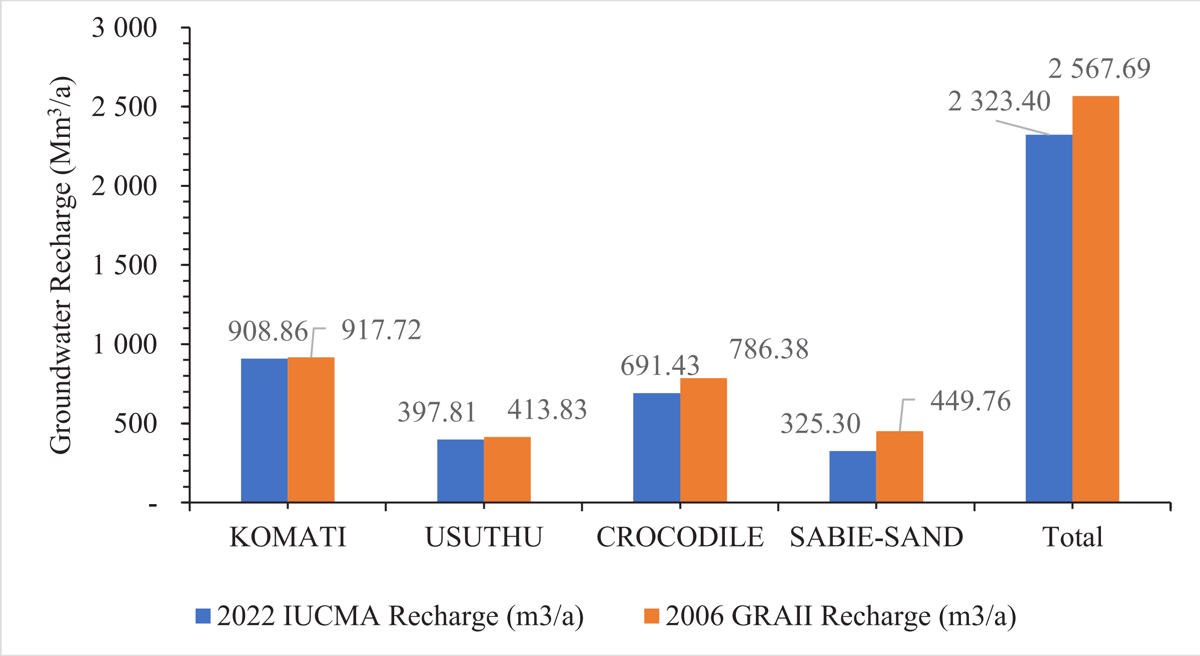


Fig. 21 The Inkomati-Usuthu WMA groundwater recharge for the year 2022 compared to the 2006 GRA II estimates.

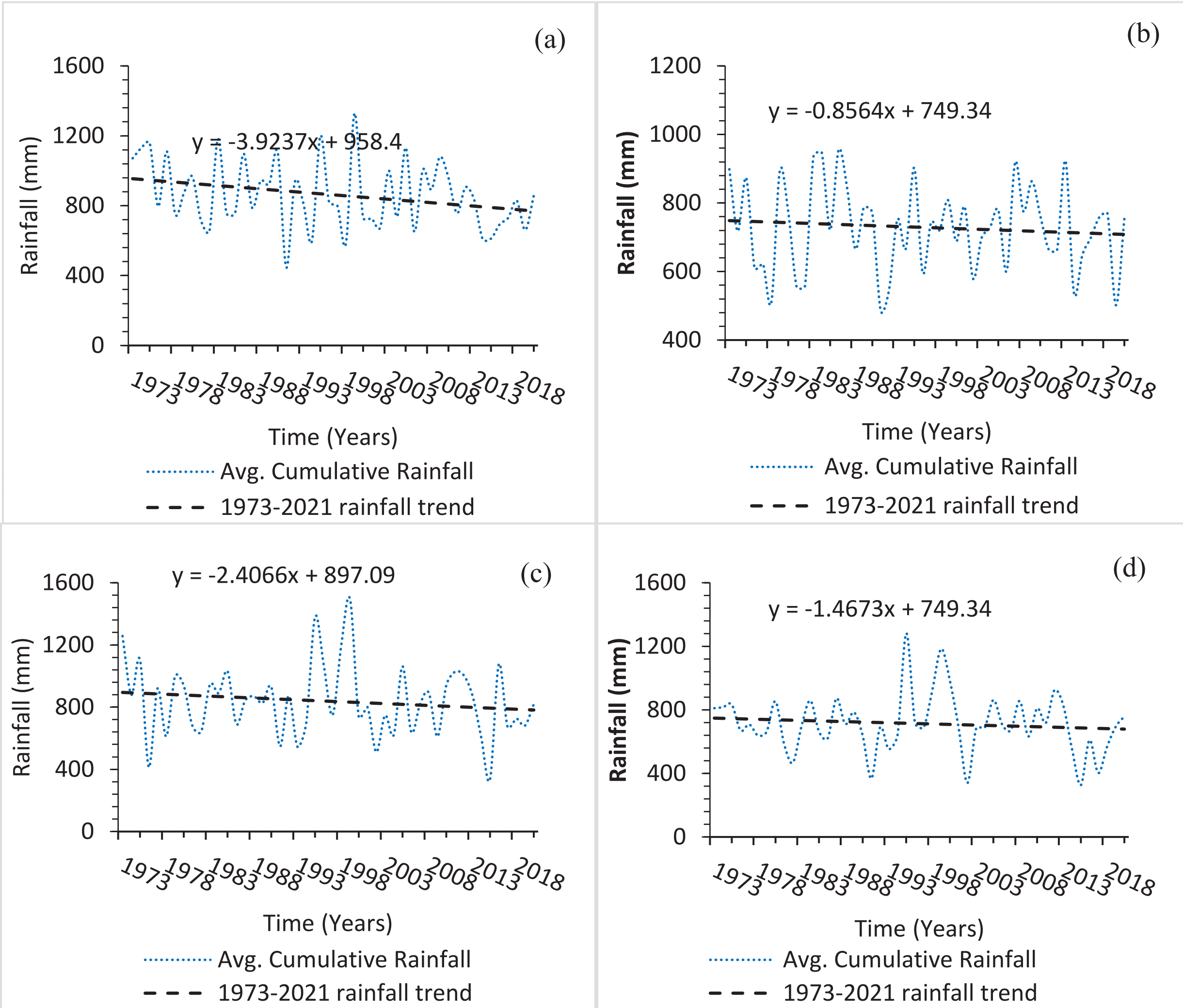


Fig. 22: Historic (48-year) rainfall in the Inkomati-Usuthu WMA a) Usuthu, b) Komati, c) Crocodile, and d Sabie-Sand

4.5. Groundwater resource potential

The results of the groundwater potential are shown in Fig. 23 against which the following key notes are made:

- Komati catchment was characterised by the highest groundwater potential of about 865.31 Mm^3/a followed by Usuthu at 357.79 Mm^3/a
- The least groundwater potential were 156.87 Mm^3/a and 93.83 Mm^3/a in the Crocodile and Sabie-Sand respectively.
- Against the two bullet points above, the entire Inkomati-Usuthu WMA had groundwater potential of 2 930.540 Mm^3/a.
- Compared to the year 2006 estimates by the GRA II
    - Komati exhibited the lowest groundwater potential decrease of about 78.72 Mm^3/a which was about 8% decrease,

- Usuthu was characterised by groundwater potential decrease of 40% (239.66 Mm^3/a)
- Crocodile and Sabie-Sand were characterised by the highest decrease of 78% (550.84 Mm^3/a) and 86% (588.52 Mm^3/a) respectively.
- The total decrease in groundwater resource potential across the entire Inkomati-Usuthu WMA was 1 456.74 Mm^3/a which is a 50% decrease from the 2006 estimates.

The decrease in groundwater potential was related to increased commercial timber plantations, increased groundwater dependency and decrease in recharge. It was indicated earlier that groundwater is traditionally relied upon when surface water resources are limited. For example, in response to the 2015/2016 drought, the South African government allocated about R2.5 billion for drought relief intervention which included what hydrogeologists considered "panic" drilling of boreholes across the country. Because of prevalent surface water restrictions, farmers, households, and businesses also followed suit and drilled boreholes to compensate for any restrictions placed on surface water use. This increased use of groundwater continued after the drought because installation of wells and the infrastructure for delivery of groundwater are a considerable investment. Additionally, it was indicated that plantations in South Africa are growing approximately at 0.5% rate annually which correspondingly leads to increased transpiration and interception (which contributes about 30% evaporation of gross precipitation).

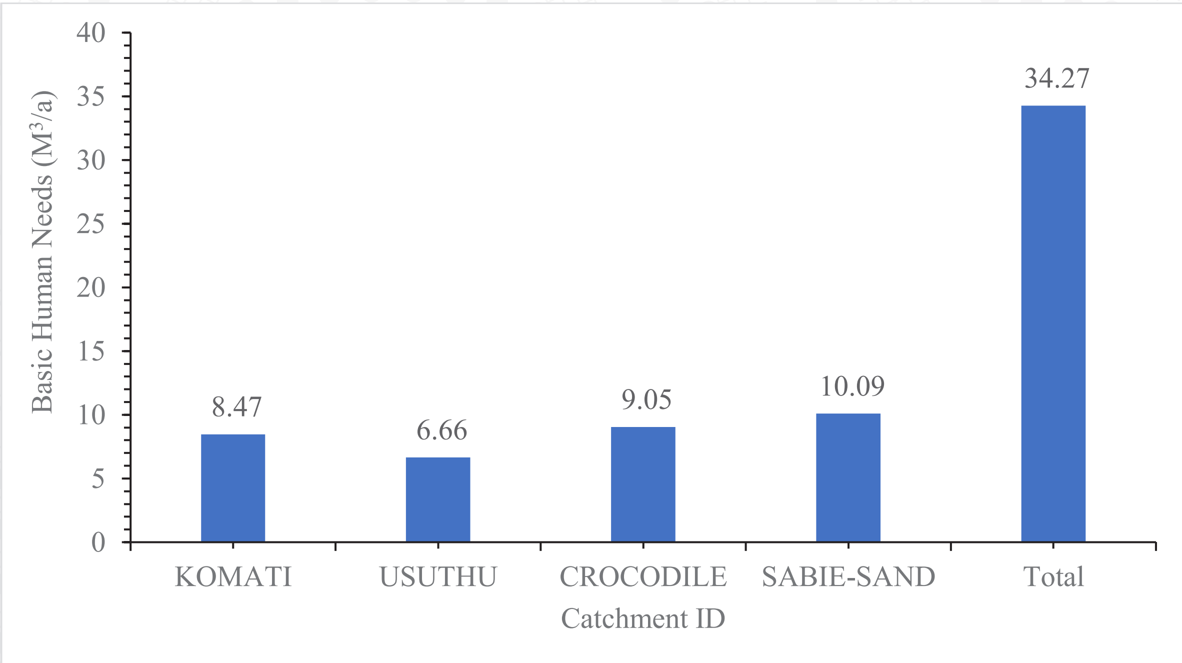


Fig. 23 Groundwater basic human needs

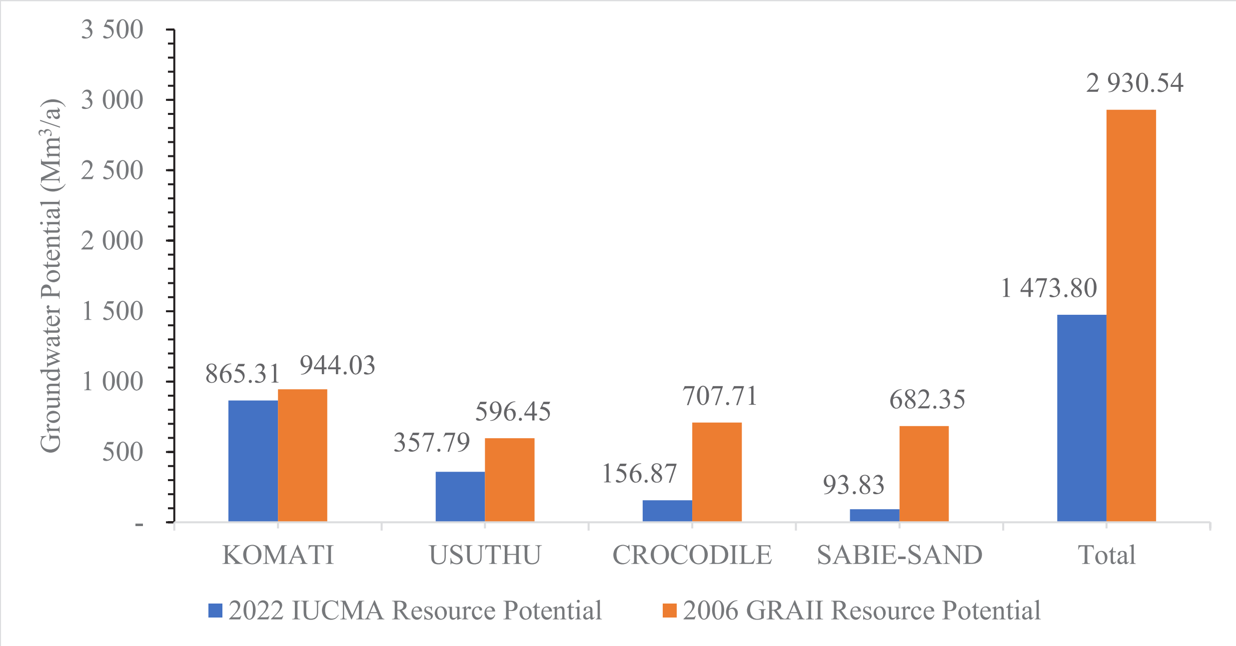


Fig. 24 Groundwater availability in the Inkomati-Usuthu WMA

The results for groundwater stress conditions and footprint are summarised in Table 6 against which the following key points are made:

- The resultant stress index values were respectively 0.03 and 0.08 for Komati and Usuthu, indicative of unstressed condition; even if some areas might be stressed, that is not ubiquitous.
- Crocodile and Sabie-Sand were characterised by stress indices of 0.91 and 0.92, respectively, which was indicative of environmental water stress.
- The catchment groundwater footprint for Komati was estimated as 5 169 km^2 (which is 59.96% of the total area) and that of Usuthu was 4 749 km^2 (which is 61.00% of the total area) resulting in $GF/BA > 1$ indicative of unstressed condition (Table 6).
- For Crocodile and Sabie-Sand, the GR were 9 483 Km^2 and 8 519 Km^2, respectively; this was 95% and 92% of the total areas for Komati and Sabie-Sand respectively resulting in $GF/BA \cong 1$, indicative of environmental water stress; consequently, groundwater resources were overused for both Crocodile and Sabie-Sand.

Table 6 Catchment groundwater footprint and stress conditions

Description		Komati	Usuthu	Crocodile	Sabie-Sand
GF (km^2)		5 169	4 749	9 483	8 519
Stress Index	Smakhtin et al. 2004	0.04	0.08	0.91	0.92
	Gleeson et al. 2012	0.6	0.6	0.91	0.92

4.6. Groundwater budget

For groundwater budget, the following key points were made:

- the outflows for Komati totalled 943.95 Mm^3/a whilst the inflow (groundwater recharge) is 908.86 Mm^3/a, indicative that outflows outweighed the inflows.
- the outflows for Usuthu was 431.169 Mm^3/a with inflows of 397.81 Mm^3/a also indicative that outflows outweighed the inflows.
- Contrarily, inflows outweigh the outflows for Crocodile and Sabie-Sand because the inflows were respectively 318.01 Mm^3/a and 682.61 Mm^3/a compared to outflows of 101.12 Mm^3/a and 165.69 Mm^3/a for Crocodile and Sabie-Sand respectively.

The above notes are indicative that the groundwater budgets are imbalanced (Table 7). Although based on the surface water balance, Wang et al. (2014) examined the water budget closures for sixteen large drainage catchments in Canada and found that the monthly water imbalance was 30%. In this study the imbalance was calculated to be 35.09 Mm^3/a (3.86%) for Komati catchment whilst 33.36 Mm^3/a (8.39%) was estimated for Usuthu catchment and that of Crocodile and Sabie-Sand are 1.28% and 2.24% respectively (Table 7). Wang et al. (2014) attributed the imbalances primarily to errors associated with quantification of the components of the water balance. Whilst this viewpoint is acknowledged, this study attributes mountain block recharge (MBR) and baseflow capture as the potential source of the observed imbalance. Baseflow capture is deliberately ruled out because evidence of capture effect should be reflected in the historic baseflow characteristics where the impact should give rise to decreasing trends in baseflow. However, as shown in Fig. 4, the slope of the linear trend line for the baseflow is near zero which effectively indicates that there is no evident historic decline of baseflow.

Table 7 A summary of groundwater trial balance for Komati and Usuthu catchments

Attributes		Komati	Usuthu	Crocodile	Sabie-Sand
Baseflow (Mm^3/a)		891.32	381.13	170.33	107.57
Change in Storage (Mm^3/a)		17.54	16.68	-4.41	-3.65
Draft (Mm^3/a)		35.09	33.36	516.69	214.09
Recharge (Mm^3/a)		908.86	397.81	691.43	325.30
Imbalance (Mm^3/a)	Mountain block Recharge	35.09	33.36		
	Baseflow capture			8.85	7.29
Imbalance (%)		3.86	8.39	1.28	2.24
Groundwater resource Potential (Mm^3/a)		865.31	357.79	156.84	93.83
Spring and wetland contribution (Mm^3/a)		3.51	3.34	51.67	21.41

Markovich et al. (2019) defined the mountain block as an area of topographically elevated and rugged terrain. A mountain block is topographically and geologically distinct from adjacent lowland areas, which are relatively flat and underlain by thick unconsolidated to semi-consolidated sediments that often form highly productive aquifers. In the Inkomati Usuthu WMA, the elevation is higher (over 2000 mamsl) and rouged in the western periphery, dropping to almost 100 mamsl in the eastern parts. Here the geology is dominated by the bushveld igneous complex (Fig. 2) which is widely characterised by joints and faults, karst network and areas divided in compartments due to dolerite dykes which can enhance yields to more than 14 l/s with springs yields as high as 1157 l/s. Apart from the northeast-trending Barberton Greenstone Belt and the northeast-trending Barberton Greenstone Belt, the adjacent lowland areas are predominantly characterised by the Archean basement comprising granitoids and gneisses which have low groundwater yields. However, it is common to get yields as high as 16 l/s with transmissivity of 1400 m²/d in structures.

Precipitation is the only water input to the mountain block; due to orographic effects, mountains receive more precipitation than the adjacent lowland areas. In the Inkomati-Usuthu WMA, rainfall varies from as high as 1445 mm/a in the escarpment and mountainous areas to rainfall as low as 470 mm in the lowveld region (the eastern and downstream portion of the catchments). Based on the range of recession constant values, it was also indicated that lowland areas are potentially characterised by higher hydraulic conductivities whilst the upland areas are characterised by lower hydraulic conductivities. This conforms to Welch and Allen (2014) conceptual model of catchment-scale vertical hydraulic conductivity zones typical of fractured crystalline rock mountain aquifer system. Haitjema and Mitchell-Bruker (2005) also gave a classification that includes a topography-controlled water table resulting from high recharge and/or low hydraulic conductivity, producing a water table high enough to sustain perennial streamflow in mountain catchments. The storage coefficients for the two catchments were in the range of confined aquifers, indicative that the source of groundwater discharge is from regional flow systems (i.e., deep aquifers) that transport groundwater from the mount block (source) and discharge it far from the source into the low-lying areas. Consequently, the observed imbalance can strongly be attributed to the MBR that is usually not accounted for in the groundwater balance equation because of its "hidden" nature. Wilson and Guan (2004) reported that 14% and 38% of annual precipitation can become mountain-block recharge and induce significant imbalances in the catchment wide groundwater accounting.

Contrarily, baseflow for Crocodile and Sabie-Sand showed evidence of decreasing baseflow (Fig. *6* and Fig. 7) due to capture which comes as result of decreasing groundwater storage (Fig. 19). This is because capture is defined as the sum of the increase in recharge and decrease in discharge (Alley et al. 1999). Subsequently, the following key points were made of the catchment level water budget:

- The total water balance for Komati was 2 753.21 m^3/a whilst that of Usuthu was 1 220.01 m^3/a whilst those of crocodile and Sabie-Sand were 1 548.56 Mm^3/a and 751.72 Mm^3/a respectively.

- Accounting for MBL, the recharge constituted the highest percentages of the groundwater budgets amounting to 35.3% and 34.3% for Usuthu and Komati respectively; draft was apportioned respective percentage of 2.73% and 1.27% (Fig. 25).
- Accounting for capture, the recharge constituted the highest percentages of the groundwater budgets amounting to 43.27% and 44.65% for Crocodile and Sabie-Sand respectively; draft was portioned respective percentage of 33.37% and 28.48% for Crocodile and Sabie-Sand respectively.
- For Usuthu, the second biggest ration went to baseflow at 31.2% followed by groundwater potential at 29.3% whist baseflow and groundwater potential are respectively 32.4% and 31.4% for Komati.
- The resultant change in storages were 0.64% and 1.37% for Komati and Usuthu, respectively.
- For Crocodile, the second biggest ration went to baseflow and groundwater potential, both at 11%. Baseflow and groundwater potential were respectively 14.31% and 13.45% for Sabie-Sand.
- The resultant change in storages were 0.29% and 0.49% for Crocodile and Sabie Sand, respectively.

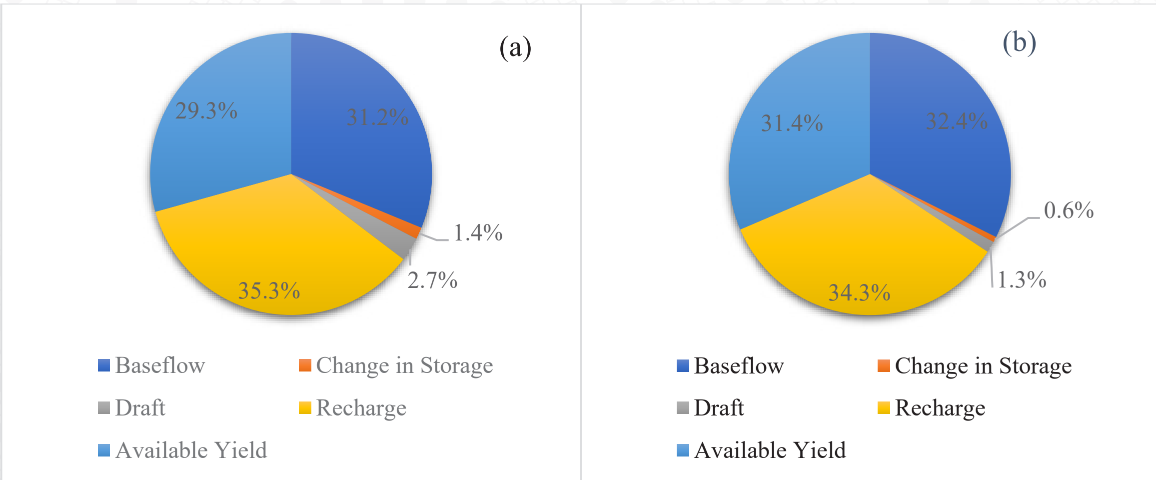
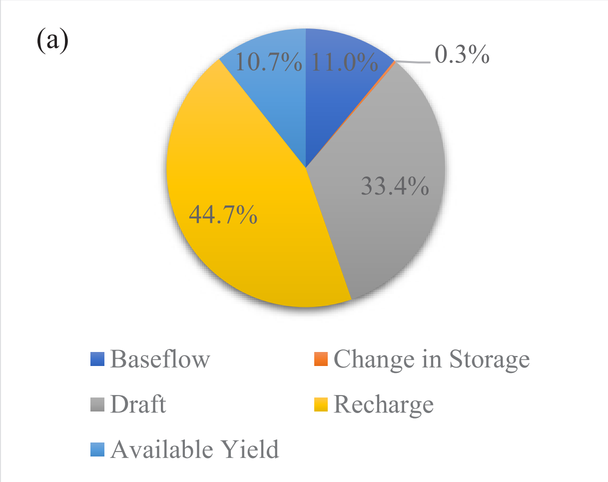


Fig. 25 A summarized groundwater balance for a) Komati catchment and b) Usuthu catchment



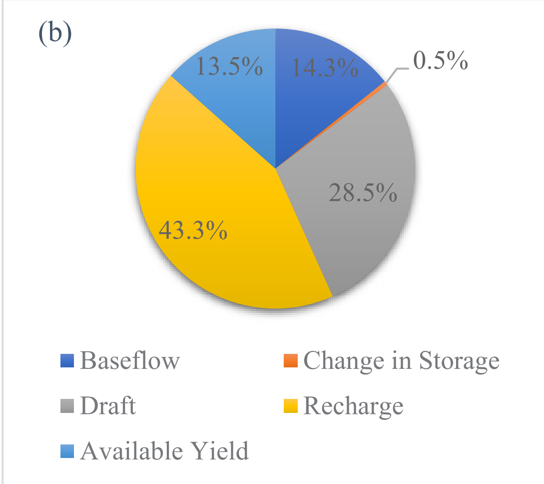


Fig. 26 A summarized groundwater balance for a) Crocodile catchment and b) Sabie-Sand catchment

5. Conclusions

The aim of this study was to provide an updated quantitative estimates of a regional groundwater budget of the Inkomati-Usuthu Water Management Area (WMA). The study followed a groundwater volume accounting approach establishing the balance between quantitative estimates of:

- groundwater recharge,
- groundwater contribution to stream flows (baseflow),
- draft (combined human and transpiration abstractions) and
- changes in groundwater storage.

The results were then compared to the 2006 results of the Groundwater Resource Assessment two (GRA II). The results established that baseflow is decreasing for Crocodile and Sabie-Sand, potentially because of high draft which accounts for 33.4% (for crocodile) and 28.5% (for Sabie Sand) of the total groundwater balance. High draft leads to capture of baseflow (environmental flow); capture is the increased recharge but decreasing groundwater contribution to streamflow due to depleting groundwater storage.

The high draft has been attributed to high amount of commercial forestry in these two catchments. This is because transpiration (difference between draft and actually abstraction sourced from the WAMRS data) was the highest for both Crocodile (513.89 Mm^3/a) and Sabie-Sand (211.36 Mm^3/a) compared to 15.44 Mm^3/a and 32.31 Mm^3/a for Komati and Usuthu respectively. For both Usuthu and Komati, baseflow is stable due to relatively small respective percentages of draft of the total groundwater balance (1.3% and 2.7%, respectively). *The implication is that the observed high groundwater draft is a threat to the ecological reserve.*

In the entire Inkomati-Usuthu WMA, groundwater recharge has decreased by 27%. With the highest decrease recorded in the Sabie-Sand and Crocodile. A 48-year cumulative rainfall data revealed that rainfall is decreasing in the Inkomati-Usuthu WMA with the highest decrease rate being in the Usuthu (at 3.92 mm/a) followed by Crocodile at 2.4 mm/a, Sabie-Sand (at 1.47 mm/a) and Komati (at 0.86 mm/a). An analysis of a land use map revealed that the highest amount of commercial forests are in the Sabie-and Komati. Consequently, both decreasing rainfall and high amount of commercial forestry are flagged as the major cause of this decrease due to canopy and litter interception. *The implication is that climate change and high amounts of commercial forestry pose a threat to the groundwater recharge.*. Nevertheless, recharge still contributes the highest percentage of the groundwater balance across the four catchments. The highest percentages are in the catchments (Crocodile and Sabie-Sand) with the highest draft because of capture.

At 865.31 Mm^3/a, the groundwater potential is higher in the Komati followed by Usuthu at 357.79 Mm^3/a. The Crocodile and Sabie Sand are characterised by the lowest groundwater potentials of 156.87 Mm^3/a and 93.83 Mm^3/a respectively. Compared to the GRA II estimates, groundwater potential has decreased by 49.71% across the Inkomati-Usuthu WMA. The biggest decreases are in the Sabie-Sand and Crocodile at 86.25% and 77.83% respectively. Usuthu and Komati characterised by decreases of 8% and 40% respectively. Compared to the 29.3% and 31.4% of Komati and Usuthu, respectively, the groundwater potential for Crocodile and Sabie-Sand only contributes 11% and 14.3% of the total groundwater budgets. *This is indicative of an environmental groundwater stress in the Crocodile and Sabie-Sand with respective groundwater footprints of 9 483 Km^2 and 8 519 Km^2 which are respectively 95% and 92% of the total areas.*

The catchment groundwater footprint for Komati was estimated as 5 169 km^2 and that of Usuthu is 4 749 km^2 (which is 60% of the total area for both catchments) resulting in $GF/BA > 1$. *This is a sign of stable groundwater resources; even if some areas might be stressed, that is not ubiquitous.*

6. References

Ahiablame L, Sheshukov AY, Rahmani V, Moriasi D (2017) Annual baseflow variations as influenced by climate variability and agricultural land use change in the Missouri River Catchment, Journal of hydrology 551:188-202, doi.org/10.1016/j.jhydrol.2017.05.055

Allwright A, Witthueser K, Cobbing J, Mallory S, Sawunyama T (2013) Development of a groundwater resource assessment methodology for South Africa: Towards a holistic approach, Water Research Commission Report 2048/1: 13

Amit H, Lyakhovsky V, Katz A, Starinsky A, Burg A (2002) Interpretation of spring recession curves, Groundwater 40(5): 543-551, doi.org/10.1111/j.1745-6584. 2002.tb02539.x

Bosch DD, Arnold JG, Allen PG, Lim KJ, Park YS (2017). Temporal variations in baseflow for the Little River experimental watershed in South Georgia, USA, Journal of Hydrology: Regional Studies 10: 110-121, doi.org/10.1016/j.ejrh.2017.02.002

Boughton WC, Askew AJ (1968) Hydrologic characteristics of catchments/Lag time for natural catchments, Lincoln College, New Zealand Agricultural Engineering Institute

Bredehoeft J.D, Papadopulos SS, Cooper HH (1982) Groundwater: The water budget myth, Scientific basis of water resource management 51: 57

Bulcock HH, Jewitt GPW (2012) Field data collection and analysis of canopy and litter interception in commercial forest plantations in the KwaZulu-Natal Midlands, South Africa, Hydrology and Earth System Sciences 16(10): 3717-3728, doi.org/10.5194/hess-16-3717-2012

Button A, Cawthorn RG (2015) Distribution of mafic sills in the Transvaal Supergroup, northeastern South Africa, Journal of the Geological Society, *172* (3): 357-367, doi:10.1144/jgs2014-101

Department of timber plantation , Fisheries and Environment (2018) State of the forests report. Pretoria, South Africa

Drucker P (2015) If you can't measure it, you can't manage it, Market Culture Blog 685-718.

Eckhardt K (2005) How to construct recursive digital filters for baseflow separation, Hydrological Processes: An International Journal 19 (2): 507-515, doi.org/10.1002/hyp.5675

Eckhardt K (2008) A comparison of baseflow indices, which were calculated with seven different baseflow separation methods, Journal of Hydrology 352 (1-2): 168-173, doi.org/10.1016/j.jhydrol.2008.01.005

Eisenlohr L, Király L, Bouzelboudjen M, Rossier Y (1997) Numerical simulation as a tool for checking the interpretation of karst spring hydrographs, Journal of Hydrology, 193 (1-4), pp.306-315, doi.org/10.1016/S0022-1694(96)03140-X

Fan Y (2019) Are catchments leaky? Wiley Interdisciplinary Reviews: Water 6 (6): e1386, https://doi.org/10.1002/wat2.1386

Roberts K (1988) The eucalypt dilemma. The eucalypt dilemma.

Feth JH (1964) Hidden recharge, Groundwater 2(4): 14–17 https://doi.org/10.1111/j.1745-6584.1964.tb01780.x.

Freeze RA, Cherry JA (1979) Groundwater, Prentice-Hall Inc. Eaglewood Cliffs, NJ.

Genereux DP, Jordan M (2006) Intercatchment groundwater flow and groundwater interaction with surface water in a lowland rainforest, Costa Rica: a review, Journal of Hydrology 320(3-4): 385-399, doi.org/10.1016/j.jhydrol.2005.07.023

Genereux DP, Jordan MT, Carbonell D (2005) A paired-watershed budget study to quantify intercatchment groundwater flow in a lowland rain forest, Costa Rica, Water Resources Research 41(4), doi.org/10.1029/2004WR003635.

Gleeson T, Wada Y, Bierkens MF, Van Beek LP (2012) Water balance of global aquifers revealed by groundwater footprint, Nature, 488(7410): 197-200, doi:10.1038/nature11295.

Hamilton LS (2008) Forests and water. FAO Timber plantation Paper, FAO, Rome (Italy)

Hannula SR, Esposito KJ, Chermak JA, Runnells DD, Keith DC, Hall LE (2003) Estimating ground water discharge by hydrograph separation, Groundwater 41(3): 368-375, doi.org/10.1111/j.1745-6584. 2003.tb02606.x

Healy RW, Cook PG (2002) Using groundwater levels to estimate recharge, Hydrogeology journal 10(1): 91-109, doi.org/10.1007/s10040-001-0178-0.

Hughes GO (1997) An analysis of baseflow recession in the Republic of South Africa (Doctoral dissertation), University of Natal, South Africa.

Hybel AM, Godskesen B, Rygaard M (2015) Selection of spatial scale for assessing impacts of groundwater-based water supply on freshwater resources, Journal of environmental management 160: 90-97, doi.org/10.1016/j.jenvman.2015.06.016

Isensee LJ, Detzel DHM, Pinheiro A, Piazza GA (2022) Extreme streamflow time series analysis: trends, record length, and persistence, Journal of Applied Water Engineering and Research 1-14, doi.org/10.1080/23249676.2022.2030254

Koïta M, Yonli HF, Soro DD, Dara AE, Vouillamoz JM (2018) Groundwater storage change estimation using combination of hydrogeophysical and groundwater table fluctuation methods in hard rock aquifers, Resources, 7(1): 5, doi.org/10.3390/resources7010005.

Le Maitre D, Seyler H, Holland M, Smith Adao L, Maherry A, Nel J, Witthuser K (2019) Strategic water source areas: Vital for South Africa's water, food, and energy security, Water Research Commission. Pretoria: South Africa.

Lohman LW (1972) Ground-Water Hydraulics. U.S. Geological Survey Profl. Paper 708.

Markovich KH, Manning AH, Condon LE, McIntosh JC (2019) Mountain-block recharge: A review of current understanding, Water Resources Research 55(11): 8278-8304, doi.org/10.1029/2019WR025676

Meza I., Rezaei EE, Siebert S, Ghazaryan G, Nouri H, Dubovyk O, Gerdener H, Herbert C, Kusche J, Popat E Rhyner J (2021) Drought risk for agricultural systems in South Africa: Drivers, spatial patterns, and implications for drought risk management, Science of the Total Environment 799: 149505, doi.org/10.1016/j.scitotenv.2021.149505

Haitjema HM, Mitchell-Bruker S (2005). Are water tables a subdued replica of the topography? Ground Water 43(6): 781–786, doi.org/10.1111/j.1745-6584. 2005.00090.x

Modica E, Buxton HT, Plummer LN (1998) Evaluating the source and residence times of groundwater seepage to streams, New Jersey Coastal Plain, Water Resour Res 34(11): 2797–2810, doi.org/10.1029/98WR02472.

Monyela BM (2017) A two-year long drought in summer 2014/2015 and 2015/2016 over South Africa, Master's thesis, University of Cape Town, South Africa.

Mukuyu P, van Koppen B, Jacobs-Mata I (2022) Operationalising hybrid water law for historical justice. WRC Report No. 3040/1/22, Water Research Commission, Pretoria, South Africa.

Pott A, Hallowes J, Backeberg G, Döckel M (2009). The challenge of water conservation and water demand management for irrigated agriculture in South Africa, Water International 34(3): 313-324, doi.org/10.1080/02508060903114657

Rumsey CA., Miller MP, Susong DD, Tillman FD, Anning DW (2015) Regional scale estimates of baseflow and factors influencing baseflow in the Upper Colorado River Catchment, Journal of Hydrology: Regional Studies 4:91-10, doi.org/10.1016/j.ejrh.2015.04.008

Santhi C, Allen PM., Muttiah RS, Arnold JG, Tuppad P (2008) Regional estimation of base flow for the conterminous United States by hydrologic landscape regions, Journal of Hydrology 351(1-2): 139-153, doi.org/10.1016/j.jhydrol.2007.12.018

Schaller MF, Fan Y (2009) River catchments as groundwater exporters and importers: Implications for water cycle and climate modeling. Journal of Geophysical Research: Atmospheres, 114(D4).

Scott, D.F., Bruijnzeel, L.A. & Mackensen, J. 2005. The hydrological and soil impacts of forestation in the tropics. In M. Bonell and L.A. Bruijnzeel, eds. Forests, water and people in the humid tropics, pp. 622–651. UNESCO International Hydrology Series. Cambridge, UK, Cambridge University Press

Scott DF, Le Maitre DC, Fairbanks DHK (1998) Timber plantation and streamflow reductions in South Africa: A reference system for assessing extent and distribution, Water SA, vol. 24(3), pp 187-199

Smakhtin V, Revenga C, Döll P (2004) A pilot global assessment of environmental water requirements and scarcity, Water International 29(3):307–317, doi.org/10.1080/02508060408691785

Stats, S.A., 2011. Statistics South Africa. Formal census

Stoate C, Boatman ND, Borralho RJ, Carvalho CR, de Snoo GR, Eden P (2001) Ecological impacts of arable intensification in Europe, Journal of Environmental Management 63(4): 337–365, doi.org/10.1006/jema.2001.0473

Teketay D (2000) Facts and experiences on Eucalypts in Ethiopia and elsewhere: Ground for making life informed decisions, Walia 2000(21): 25-46.

Thorling, L., Hansen, B., Langtofte, C., Brüsch, W., Møller, R.R. and Mielby, S., 2012. Grundvand: Status og Udvikling 1989–2011 (groundwater: Status and Development 1989–2011). Technical report, Geological Survey of Denmark, and Greenland.

Toebes C, Morrissey WB, Shorter R, Hendy M (1969) Baseflow recession curves: Handbook of hydrological procedures, In Proc 8.

Toth J (1963) A theoretical analysis of groundwater flow in small drainage catchments, Journal of geophysical research, 68(16): 4795-4812, doi.org/10.1029/JZ068i016p04795

Vashisht AK, Bam B (2013) Formulating the spring discharge-function for the recession period by analyzing its recession curve: A case study of the Ranichauri spring (India), Journal of earth system science, 122(5): 1313-1323, doi.org/10.1007/s12040-013-0356-1.

Viviroli D, Weingartner R, Messerli B (2003) Assessing the hydrological significance of the world's mountains, Mountain research and Development 23(1): 32-40, doi.org/10.1659/0276-4741(2003)023[0032: ATHSOT]2.0.CO;2.

Wang C, Shang S, Jia D, Han Y, Sauvage S, Sánchez-Pérez JM, Kuramochi K, Hatano R (2018) Integrated effects of land use and topography on streamflow response to precipitation in an agriculture-forest dominated northern watershed, Water 10(5): 633, doi.org/10.3390/w10050633.

Wang D, Cai X (2009) Detecting human interferences to low flows through base flow recession analysis, Water resources research 45(7), doi.org/10.1029/2009WR007819.

Weber KA, Perry RG (2006) Groundwater abstraction impacts on spring flow and base flow in the Hillsborough River Catchment, Florida, USA. Hydrogeology Journal 14(7): 1252-1264, doi.org/10.1007/s10040-006-0040-5

Welch LA, Allen DM (2014) Hydraulic conductivity characteristics in mountains and implications for conceptualizing bedrock groundwater flow, Hydrogeology Journal 22(5): 1003-1026, doi.org/10.1007/s10040-014-1121-5

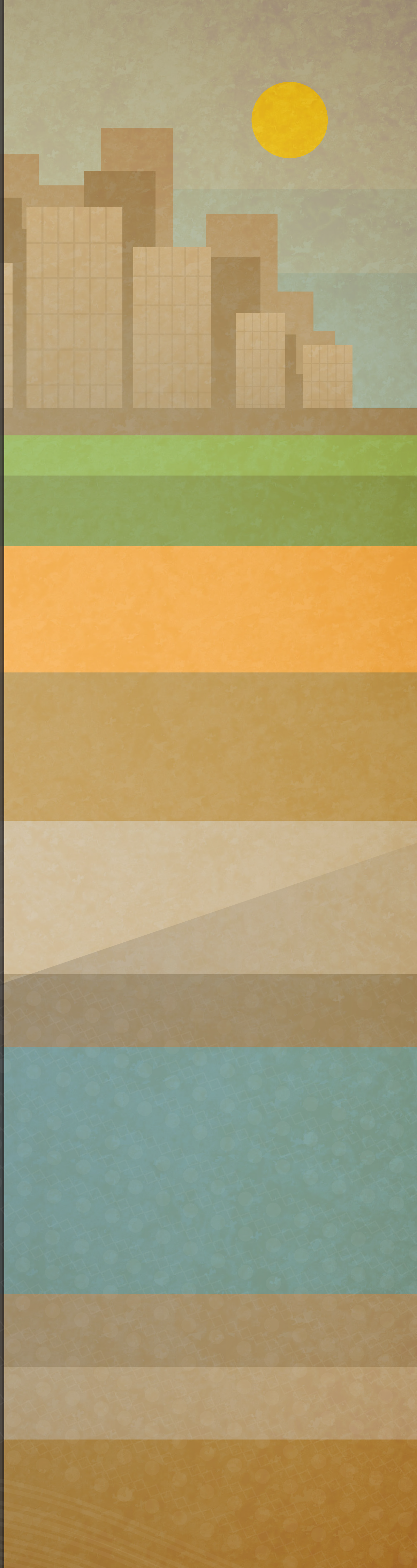
Wilson J.L, Guan H (2004) Mountain-block hydrology and mountain-front recharge. Groundwater recharge in a desert environment: The Southwestern United States 9: 113-137.

Winter TC, Harvey JW, Franke OL, Alley WM. (1998) Groundwater and surface water: A single resource, US Geol Surv Circ. 1139.

Wittenberg H (2003) Effects of season and man-made changes on baseflow and flow recession: case studies, Hydrological Processes 17(11): 2113-2123, doi.org/10.1002/hyp.1324

SLOGAN:

“INKOMATI-USUTHU CMA, YOUR PARTNER IN WATER MANAGEMENT”



INKOMATI-USUTHU
CATCHMENT MANAGEMENT AGENCY

Groundwater

Resource Accounting for the
Inkomati-Usuthu Water Management Area
in Mpumalanga, South Africa

Implementation of the
Groundwater Strategy

2023

Tel: 013 753 9000

www.iucma.co.za

IUCMA

Inkomati-Usuthu CMA

2nd floor ABSA Square Building
20 Paul Kruger Street
Mbombela
1200

QR CODE
FOR THE
IUCMA
WEBSITE